UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

# PROGRESS REPORT ON RESULTS OF STUDIES ON DESIGN OF STABLE CHANNELS

Hydraulic Laboratory Report No. Hyd-352

ENGINEERING LABORATORIES BRANCH
and
OFFICE OF CHIEF DESIGNING ENGINEER



DESIGN AND CONSTRUCTION DIVISION
DENVER, COLORADO

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Subject: Progress report on results of studies on the design of stable channels

## INTRODUCTION

Since January 1950 the Bureau of Reclamation has conducted a program to investigate new and improved methods in the design of unlined canals. Particular emphasis has been given during this period to methods of obtaining a rational solution to the problem of sediment transportation as it relates to design of unlined canals.

This paper summarizes the results of the investigation up to about June 1952. In general, the principal progress made in these studies has been along three general lines: (1) the clarification of the general principles of stable channel design, the knowledge of which has long been in an unsatisfactory state, (2) the working out of a tentative method of designing unlined earth canals to insure freedom from scour, and (3) the development of an analysis of the channel shape for certain conditions involving minimum excavation quantities. It has so far not been possible to study many important aspects of the general problem, especially that involving the design of canals transporting considerable coarse sediment. It is believed, however, that considerable improvement in design procedure has been accomplished, and that a better understanding of the general problem has been gained, so that greater progress in working out future developments will be possible.

In studying the general principles of stable canal design, an intensive study of the literature on this subject from all over the world has been made. It has been found that the subject is a very complex one, and that a great variety of conditions exists which makes the best solution in many cases differ widely from those where other conditions prevail. A complete solution of the problem must therefore include an analysis of all these conditions and a determination of the solution applicable to each. Since the canals under study by this

Bureau cover a large part of the whole range of conditions, to completely answer the Bureau's need, practically the whole range of the problem must be studied. Fortunately, the previous studies made throughout the world cover a wide range of conditions, and it has been possible, from a study of the treatments developed for the various conditions, to work out an analysis of the whole field. It is believed that this gives a much better understanding of the problem as a whole and the relation of the various phases of it to each other, which should greatly expedite progress on future work in this field.

The first part of this paper will therefore consider the general aspects of the problem, such as the fundamental principles involved, the conditions encountered and the type of solutions required for each. This will be exemplified by the history of the past development of the science, in the various countries, and the trend which the studies in these countries took as a result of the predominant local conditions in them. The second part of the report covers the principles involved in the protection of canals against scour from the flowing water. It presents the quantitative relations developed, and illustrates their application to canal design. The third part deals with the development of an analysis of the channel shapes for canals involving minimum excavation quantities.

## GENERAL ASPECTS OF STABLE CHANNEL DESIGN

### Definitions and First Principles

Since the term "stable channels" as used in this report has a rather special meaning, it is desirable at the outset of the discussion to define the term and explain its limitations. A "stable channel," as used in this paper, is an unlined earth channel for carrying water, the banks and bed of which are not scoured by the moving water, and in which objectionable deposits of sediment do not occur. Sediment has been defined as 2/ "Fragmental material transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agents; any detrital accumulation, such as loess." This report is concerned only with the sediment aspects of earth channel design, and deals with stability of the channel only from the standpoint of the movement or deposition of earth materials by the flowing water. It does not deal with the stability of the banks from sloughing or sliding down into the canal. The latter is a problem in soil mechanics, for which the principles have been to a large extent developed. Nor does the subject of

2/ Transactions, American Geophysical Union, Vol. 28, December 1947, p. 936.

stable channels deal, except to a very limited extent, with the problems of flow of water through the canals, which are problems in canal hydraulics.

The problem of designing canals in which neither scour nor objectionable deposits occur has two principal aspects: (1) the problem of scour of the banks and bed, and (2) the problem of objectionable sediment deposits. Where earth canals are constructed it is desired that the shape and position of the banks and bed will not change, as difficulties of numerous kinds arise from such changes. When the water is turned in, it is hoped that it will not carry sediment which will cause objectionable deposits someplace in the canal. Such deposits may cause an undesirable loss of discharge capacity of the canal, or may set up currents which cause the banks to be scoured. Not all deposits of sediment in a canal are objectionable; some are beneficial, such as those which reduce the leakage from the canal through percolation through the banks and bed, or cause the banks and bed to better resist scour.

## Three Classes of Unstable Channels

From the standpoint of stable channels, as defined in this report, there are three classes of unstable channels: (1) channels where the banks and/or bed are scoured without objectionable deposits being formed, (2) channels in which objectionable sediment deposits occur without scour being produced, and (3) channels in which scour and objectionable deposits are both present. 3/

With sediment-free water only the first class of instability can occur, although this water can obtain a load of sediment by scouring the banks and/or bed and thus cease to be sediment-free. The first class of instability (scour without deposit) can also occur from water carrying sediment, especially when the amount of sediment carried by the water is small.

The second class of instability (deposit without scour) can only occur from the sediment brought into the canal with the flowing water or scoured from the banks and bed of a channel farther upstream. A common case is a lined canal or one cut through a scour-resistant material, into which large quantities of coarse sediment enter with the inflowing water.

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3/ Since this paper was written it has been discovered that these three classifications have been previously pointed out by A. R. Thomas in the 1945 Annual Report of the Central Board of Irrigation of India.

The third class of instability usually occurs when water containing large quantities of coarse sediment is introduced into a canal, the bank and bed of which are composed of material which has low scour resistance.

For prevention of instability of the first class, an analysis of scouring action only is necessary. For prevention of instability of the second class, it usually is necessary to insure that the sediment brought into the canal at its upstream end is carried out at the downstream end. The basic analysis of this problem must therefore be from the approach of sediment transportation. The presentation of instability of the third class involves the analysis of the combination of the scour and transportation problems.

## General Aspects of Sediment Transportation in Canals

Although the basic analysis of the problems of objectionable deposits in canals must eventually be along the line of a quantitative analysis of sediment transportation, a great deal can be learned from a qualitative study of sediment transportation in canals. In most cases objectionable deposits in canals result from sediment composed of sand or larger-sized particles. In main canals, except for the formation of berms, which is usually a minor difficulty, if the growth of vegetation is prevented, the silt and clay size particles usually do not cause trouble, as in general they pass through the canal with the water and flow out onto the fields. In a relatively few cases, such as in the loess region of China and the Rio Puerco region in New Mexico, where very high concentrations of fine sediment occur, a special analysis of the problem will be necessary. In many cases where the material likely to cause objectionable deposits is composed of sand and larger-size particles, the laws of sediment transportation in their present state of development can be used. In using these laws, however, it is desirable to remember that they are usually working out for equilibrium conditions, for streams where the entire bed is covered with transportable material, and that in canals a condition is frequently encountered where only part of the bed is so covered.

Every canal when flowing at its design discharge has a definite maximum capacity to carry sediment of a certain size range. If more of the material of this size range is fed into it, deposits will occur. If less than this amount is fed in, it will be transported on down the canal. In regions where the sediment loads carried by the streams are large, canals are frequently supplied with more sediment than they will carry and harmful deposits result. Where the streams carry light sediment loads, the condition where canals receive less than they can carry is more frequent and sediment troubles are usually of a minor nature. In India and Pakistan, where the sediment loads are usually high, the first condition is encountered in some localities, but in most cases in this country, the second condition exists and trouble from sediment deposition is not so important.

To understand these conditions more clearly, consider a canal of uniform slope and cross section carrying a uniform flow of clear water, with a nonerodible bed and banks. Assume that a small quantity of sediment, of a small enough size to be readily moved, is fed into the upper end of this canal at a continuous uniform rate. After sufficient time has elapsed for equilibrium to be obtained, this material will be continuously moved down the canal and out at the lower end, at the same rate as it is introduced at the upper end. Under these conditions, small patches of the material will form on the bed of the canal, from which particles are alternately moved away or deposited as the velocity fluctuates, due to turbulence. Suppose that the rate at which the sediment is added is increased. After equilibrium for this new rate is established, the sediment will be discharged out of the canal at its lower end at this new rate. Under this condition, there will also be patches of sediment on the bed of the canal, from which the sediment will be alternately picked up and deposited, but in this case, the area covered by these patches will be greater than in the former case. In both cases, the area will be such that the turbulent currentswill just move along the canal the amount of material introduced at the upper end. This will also be the case for still further increases in rate of introduction, until the patches cover the entire bottom of the canal. When this point is reached, the turbulence cannot pick up any more sediment and move it along, and the amount carried out at the lower end of the canal is the maximum possible amount of movement under these conditions. If material is introduced into the upper end of the canal at a still greater rate than this maximum transportation rate, sediment will be deposited in the canal, at a rate equal to the difference between the introduction rate and the maximum transportation rate.

The maximum transporation rate can be changed by (1) changing the discharge of the canal, or (2) altering its slope, or (3) its shape, or (4) changing the particle size of the sediment. One of the most important problems of design of stable channels carrying sediment therefore involves the determination of the hydraulic factors for a canal which will have a transporting capacity sufficient to carry the material introduced at the upper end.

## HISTORY OF THE DEVELOPMENT OF STABLE CHANNEL SCIENCE

Contributions to the science of stable channels have come from a number of different countries. For the most part the contributions were developments toward the solution of the type of instability prevalent in that country, and the type depended upon the conditions under which irrigation was carried out there. The most extensive studies of the stable channel problem were made in India and Pakistan, where the greatest development of modern irrigation has taken place. A smaller amount of study has been given to the subject in the United States and some investigation has also been carried on in various other countries. In the following sections is given a brief summary of these developments.

Developments in India and Pakistan. Although a wide range of conditions of irrigation exists in India and Pakistan, the contributions to the science of stable channels came largely from the northern parts of those countries, 4/ where large rivers flow out of the Himalaya Mountains onto a wide, gently sloping section of arid but fertile plain, presenting probably the most favorable conditions for irrigation to be found anywhere in this world. These rivers carry heavy loads of sediment, ranging from coarse gravel to clay sizes. Most of the streams carry large quantities of sand, much of which, in the early days of irrigation, was taken into the canals. These canals were usually unlined and passed through the alluvial material of which the plains were formed, which had little resistance to erosion. In these canals the predominant condition of instability was of the third type, both scour and deposit, and the developments worked out were for the treatment of this condition.

One of the earliest major contributions to the science of stable channels was that of Kennedy. 5/ From a study of the discharge and depth of 22 canals of the Upper Bari Doab system, which channels he believed to be stable, Kennedy developed his famous formula

$$V = CD^n$$

where V is the mean velocity of flow in feet per second, D is the canal depth in feet, and C and n are constants. For these canals, C had a value of 0.84 and n of 0.64, but Kennedy believed that the value of C would vary in different systems but that n would differ only slightly. Kennedy prepared a set of diagrams involving his relations, which were widely used in the design of canals and were very beneficial in reducing sediment difficulties.

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4/ Since the separation of Pakistan from India has occurred since most of the reports were written on which much of the information from these countries in this report is based, it has not been practicable to determine in which country the work was done, and cases will unavoidably occur in this report where India will be referred to, when Pakistan should have been mentioned.

5/ "The Prevention of Silting in Irrigation Canals," R. G. Kennedy, Proceedings of the Institution of Civil Engineers, Vol. 119, 1895, pp. 281-290.

Mr. Kennedy's relation gave a value of canal depth, but did not specify a width. The next important step was proposed by Lindley, 6/ who derived, from observations on the Upper Chenab Canal System, the relations

$$V = 0.95D^{0.57}$$

and

$$V = 0.57W^{0.355}$$

where W is the average width of the canal.

These equations supplied a method of computing the canal width. The next major development was the series of articles by Gerald Lacey. 7/8/9/10/ In these articles Lacey developed the relations between all of the variables involved in stable channels and equations expressing them. The equations can be expressed in a number of ways, one of which is as follows:

$$P = 2.67Q^{1/2}$$
$$R = 0.47(Q/f)^{1/3}$$
$$A = 1.26Q^{5/6}/f^{1/3}$$
$$V = 0.79Q^{1/6}f^{1/3}$$
$$S = 0.00055f^{5/3}/Q^{1/6}$$

In these equations, f is a "silt factor," which is not very clearly defined.

The concentration of the sediment load or charge was brought into the equations of stable channels, apparently for the first time,

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6/ "Regime Channels," E. S. Lindley, Proceedings Punjab Engineering Congress, Vol. 7, 1919, pp. 63-74.

7/ "Stable Channels in Alluvium," Gerald Lacey, Proceedings of the Institution of Civil Engineers, Vol. 229, 1930, pp. 259-384.

8/ "Uniform Flow in Alluvial Rivers and Canals," Gerald Lacey, Proceedings of the Institution of Civil Engineers, Vol. 237, 1933-34, p. 421.

9/ "Regime Flow in Incoherent Alluvium," Gerald Lacey, Central Board of Irrigation (Government of India) Publication No. 20, 1939.

10/ "A General Theory of Flow in Alluvium," Gerald Lacey, Journal of the Institution of Civil Engineers, Paper 5515, Vol. 27, 1948, p. 16.

by Sir Claude Inglis. 11/12/ His relations, which follow, were based on experiments carried out at the Indian Waterways Experiment Station at Poona, India:

$$b = A_1 \frac{Q^{1/2}}{g^{1/3}\ \gamma^{1/2}} \left(\frac{XV_s}{m}\right)^{1/4}$$

$$A = A_2 \frac{\gamma^{1/36}}{g^{7/18}} \frac{Q^{5/6}}{(mXV_s)^{1/12}}$$

$$d = A_4 \frac{\gamma^{1/9}}{g^{1/18}} \frac{Q^{1/3} m^{1/6}}{(XV_s)^{1/3}}$$

$$S = A_5 \frac{(mXV_s)^{5/12}}{\gamma^{5/36} g^{1/18} Q^{1/6}}$$

where b is the surface width, d the mean depth, X is the concentration or charge, $V_s$ is the terminal velocity of the bed material, falling through water, m is the effective mean diameter of bed material, $A_1$, $A_2$, $A_4$, and $A_5$ are unevaluated coefficients, and the other symbols have the usual meanings.

In a recent paper 13/ and book, 14/ T. Blench has proposed a set of relations, which take into account the difference in the types of material found on the bed and banks of the canal. His design equations are:

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11/ "The Effect of Variations in Charge and Grade on the Slopes and Shapes of Channels," Sir C. Inglis, Proceedings International Association for Hydraulic Structures Research, Third Meeting, Grenoble, France, 1949.

12/ "The Behavior and Control of Rivers and Canals," Sir C. Inglis, Part I, pp. 136-137, Central Waterpower Irrigation and Navigation Research Station, Poona, India, Research Publication No. 13.

13/ "Regime Theory for Self-Formed Sediment-Bearing Channels," Proceedings, ASCE, Separate No. 70, 1951.

14/ "Hydraulics of Sediment-Bearing Canals and Rivers," T. Blench.

$$W = \sqrt{\frac{b}{s}}\ Q^{1/2}$$

$$D = \sqrt[3]{\frac{s}{b^2}}\ Q^{1/3}$$

$$S = \frac{b^{5/6} s^{1/12}}{2080 Q^{1/6}}$$

where D is the depth above the sand bed, W is the width, which, multiplied by the depth D, gives the cross-sectional area of flow, S is the energy gradient, b is a coefficient which depends on the nature of the bed material and ranges from about 0.6 to about 1.25, and s is a coefficient which depends on the nature of the material composing the sides and ranges from 0.3 for glacial till to 0.05 to 0.10 for sand sides of rivers below tide level.

All of these papers discussed the general aspects of stable channels and each added to the available knowledge some ideas further clarifying the problem. The authors were all men of extensive experience in the plains area of India and Pakistan previously mentioned and their point of view was therefore naturally very largely influenced by this fact. The work of Kennedy, since it involved no width relation, might be applicable to either Class 2 or Class 3 instability (objectionable deposit and both scour and objectionable deposit, respectively), but Lindley's and Lacey's relations were applicable only to Class 3 conditions (both scour and objectionable deposit). Blench's treatment covers both Class 2 and Class 3. None of them are directly applicable to the conditions of Class 1, where scour only is present.

Because of the great volume of material on this subject from India and Pakistan, the fact that most of it concerned conditions which were not widely prevalent in the work of the Bureau of Reclamation which was under study, and because insufficient time has been available, a complete review of this literature has not been made. It is possible, therefore, that valuable contributions from there have been overlooked. It is planned that more thorough study of this literature will be made, especially when opportunity is available for a thorough study of Class 2 and Class 3 conditions.

For those who wish to study more deeply into the problem of stable channels, good summaries of the studies made in India are found in papers by Inglis 15/ and by Malhotra and Ahuja. 16/ References to the work of Woods, 17/ Inglis, 18/ Thomas, 19/ and Das 20/ are also given.

Developments in the United States. In the United States a wide variety of conditions affecting stable channel designs is found on various irrigation developments. The majority of projects which have been built in the past get their water supply from streams with mountainous drainage areas, which carry comparatively little sediment, or are supplied from storage reservoirs. On these sediment is usually a minor problem. On streams in the southwestern part of the country, such as the Colorado or Rio Grande, heavy sediment loads are encountered, and where water is used without previous storage, considerable sediment usually enters the canal. Most of the canals under study by this Bureau involve comparatively sediment-free water or water drawn from storage, but some severe sand problems will be encountered in the Loup and Republican River watersheds of Nebraska. Most of the problems on the future canals will be to prevent Class 1 instability, but the Loup and Republican River problems are likely to fall into Class 3 or possibly Class 2.

The first important contribution to the science of stable channels in the United States is found in Irrigation Canals and Other Irrigation Works by P. J. Flynn, 1892. He gives a large number of examples of canals constructed in various types of material, which carry relatively high velocities. The next major contribution was that by B. A. Etcheverry, who published in 1915 his book Irrigation Practice and Engineering, Volume II, "The Conveyance of Water," a table of maximum mean velocities safe against erosion. The next important contribution

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15/ "Historical Note on Empirical Equations Developed by Engineers in India for Flow of Water and Sand in Alluvial Channels," Sir Claude Inglis, Proceedings International Association of Hydraulic Research, 1948.

16/ "A Review of the Progress on Theory and Design of Stable Channels in Alluvium," S. L. Malhotra and P. R. Ahuja, United Nations (ECAFE) Technical Conference on Flood Control, New Delhi, 1951.

17/ "A New Hydraulic Formula for Silting Velocity," Kennedy data, F. W. Wood, The Engineer, Vol. 143, June 17, 1927.

18/ "The Behavior and Control of Rivers and Canals," Sir Claude Inglis, Central Water Power, Irrigation and Navigation Research Station, Publication No. 13.

19/ "Slope Formulas for Rivers and Canals," A. R. Thomas, Annual Report, Central Board of Irrigation of India, 1945, pp. 62-71.

20/ "Theory of Flow of Water and Universal Hydraulic Diagrams," Ishar Das, Central Board of Irrigation Journal, March 1950, pp. 151-162.

was the paper "Permissible Canal Velocities," by S. Fortier and Fred C. Scobey, 21/ who gave permissible velocities for canals carrying clear water, water with colloidal silts, and water transporting abrasive material. It will be noted that most of these data are concerned with the problem of scour, or with Class 1, instability, but do not deal with Class 2 or Class 3.

In 1929 studies were undertaken by the Bureau of Reclamation to secure the most economical design for the All-American Canal, using water from the Lower Colorado River, which carried a heavy sediment load. A thorough review of the available literature was made, and an attempt was made to formulate the principles governing stable channels. The construction of the canal was ordered before this study was carried to the point of securing quantitative relations suitable for design. The principles as deduced, expressed in general terms, were published in "Stable Channels in Erodible Material," by E. W. Lane. 22/ These studies were resumed in 1950, leading to the progress covered in this report.

Developments in Other Countries. The canals of Egypt are located in the Nile Valley or the Nile Delta, a land of very flat slopes. The river carries comparatively light loads of fine sediment. The experience in Egypt is presented in Irrigation Practice in Egypt, Molesworth and Yenedunia, 1922, in the form of diagrams and formulae showing the sections of canals which had proved to be stable under Egyptian conditions.

In 1930 there appeared in a Russian magazine, Gedrotekhnecheskoe Stroitelstov, an anonymous article entitled "The Maximum Permissible Mean Velocity in Open Channels," which gave the velocities above which scour would be produced in noncohesive material of a wide range of particle sizes and various kinds of cohesive soil. It also gave the variation of these values with canal depth.

## FORCES CAUSING SCOUR ON CANAL BANKS AND BED

The first step in analyzing the problem of securing freedom from scour in canals appears to be a consideration of the forces causing such scour.

Scour on the banks and bed of a canal takes place when the particles composing the sides and bottom are acted upon by forces sufficient to cause them to move. As pointed out in the report on the

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21/ Transactions ASCE, Vol. 89, 1926, pp. 940-984.

22/ Transactions ASCE, Vol. 102, 1937, pp. 123-194.

earlier studies of this Bureau in stable channels, 23/ when a particle is resting on a level bottom of a canal, the force acting to cause motion is that due to the motion of the water past the particle. If scour is to be prevented, this motion must not be rapid enough to produce forces on the particle sufficiently large to cause it to move. If a particle is on a sloping side of a canal, it is acted on, not only by the water, but also by the force of gravity, which tends to make it roll or slide down this slope. The force tending to cause the downward motion is the component, in the direction of the slope, of the force of gravity acting on the particle. If the resultant of the force due to the motion of the water, and the component of the force of gravity acting on the particle, is large enough, the particle will move. Where cohesion of the particles is present, for the particles to be moved, the forces acting must be sufficient to overcome this also. Where the particles are sufficiently small they may be carried away by being taken into suspension.

For example, consider a particle, too large to be taken into suspension, resting on the perimeter of the cross section of a canal in noncohesive material, as shown in Figure 1. If the bottom of the canal is level, as at A, motion will occur when the water moves past the particle with sufficient velocity to produce a force, F, large enough to cause it to roll or slide longitudinally down the canal. If the particle is on the side of the canal, as at B, there will act on it a force $F_2$, due to the longitudinal motion of the water flowing down the canal, and the force of gravity, G, which will have a component, $G_2$, acting in the direction of the slope of the canal bank, and another component, $G_1$, acting perpendicular to the bank. Motion of this particle will occur when the resultant, R, of the longitudinal force, $F_2$, and the gravity component, $G_2$, is sufficiently large to cause motion. This force, R, will be less than the force, F, since the component of the weight, $G_1$, acting perpendicular to the bank is smaller than the weight, G, which acts perpendicular to the bottom on the particle at A.

## TRACTIVE FORCE DISTRIBUTION ON SIDES AND BED OF A CANAL

The movement of material on the banks and bed of a canal, where cohesion is not present, depends upon the steepness of the side slope and the velocity and turbulence near the banks and bed. The forces due to the slope of the sides are easily designated, but those due to the velocity and turbulence near the boundaries are difficult to determine, due to the high rate of change of velocity with distance above the bed and the rapid fluctuations of velocity due to the turbulence in the flowing water. Another complicating factor is the presence of the boundary layer. The possibility of reaching a satisfactory analysis from a study of the

23/ Transactions ASCE, Vol. 102, 1937, p. 134.

velocities acting on the particles, therefore, did not seem promising and instead the approach from the standpoint of tractive force or shear was adopted.

Briefly stated, tractive force or shear is the force which the water exerts on the periphery of a channel due to the motion of the water, and it acts in the direction of flow, not normal to the surface, as does the static water pressure. It is not the force on a single particle but rather the force exerted over a certain area of the bed or banks. This concept was first introduced into hydraulic literature by M. P. du Boys. 24/

The shear or tractive force is equal to and in the opposite direction to the force which the bed exerts on the flowing water. If no force was exerted by the banks or bed on the water, it would continue to accelerate, just as a frictionless ball rolling down an inclined plane. In a uniform channel of constant slope, in which the water is moving in a state of steady, uniform flow, the water is not accelerating because the force tending to prevent motion is equal to the force causing motion. The tractive force under these conditions is therefore equal to the force tending to cause the water to move. This force is the component, in the direction of flow, of the weight of the water. In a channel of infinite width and length with uniform slope, the tractive force exerted by the water on a square foot of area is the component in the direction of flow of the weight of the water above that square foot. The weight of this water is equal to wD where w is the unit weight of the water and D is the depth of flow. The component of this weight in the direction of flow is this weight multiplied by the slope, S, or wDS. As will be shown later, in most canals of the shape used in irrigation, the tractive force near the middle of the bottom very closely approaches that in an infinitely wide channel or to this value wDS.

In trapezoidal channels, such as are commonly used in hydraulic engineering work, the tractive force acting is not uniformly distributed over the bed and banks, and in analyzing scour in canals on the basis of tractive force it is therefore necessary to determine how this force is distributed. In this study a condition of similitude of tractive force distribution in canal cross sections has been assumed.

Consider, for example, the cross section of a trapezoidal canal with a bottom width, B, a depth, D, and side slopes of 1-1/2:1. Under the above assumption, consider an area of the bed in the center of the channel. The tractive force on this area will bear a fixed relation to the mean tractive force on the periphery of the section. For

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24/ du Boys, M. P., "The Rhone and Streams with Movable Beds," Annals des Pontes et Chaussees, Tome XVIII, 1879.

in all canals having the same ratio of B to D and the same side slopes, the tractive force distribution will be similar, that is, the tractive force at any point in one cross section will be similar to that in any other point with the corresponding position in any other similar section. Thus, if we can get the tractive force distribution in any canal, we will have the distribution in any other canal of similar cross section. The foregoing discussion has dealt with trapezoidal channels, but it can be applied also to other shapes of channels.

## ADDITIONAL EVIDENCE SUPPORTING TRACTIVE FORCE ANALYSIS

One of the advantages of the use of the tractive force analysis rather than the limiting velocity approach for the design of large canals is that it indicates why higher velocities are safer in large canals than in small ones. This fact that higher velocities can be used in large canals has been known for many years. In his book Working Data for Irrigation Engineers--1915, Moritz states "It is a well known fact that small canals erode at a lower mean velocity than large canals." In their paper on "Permissible Canal Velocities" 21/ Fortier and Scobey also indicate this fact and include a correction for this effect. Ivan E. Houk in his discussion of this paper also brings out the increase in scouring velocity with depth. In the USSR article, the variation of limiting velocity with depth is given on Tables 6 and 8 which agrees so closely with that which would be produced by a constant value of tractive force that it seems possible that the corrections were derived from this assumption. A table of canal dimensions based on extensive experience of Bureau personnel was recently drawn up for use in design of canals in earth on the Columbia Basin Project. When studied on the basis of tractive force analysis, they showed nearly constant values of tractive force, where the conditions were constant. Limitations of space prevent a detailed discussion of this subject, but the available information strongly supports the claim of superiority of the use of limiting tractive force over limiting velocity as a basis for canal design.

### Determination of Tractive Force Distribution from Velocity Distribution

Studies to determine the distribution of the tractive force or shear on the bottom and sides of canals were carried on along two lines. One was based on an analysis of the measured velocity distribution in such channels. The other was a mathematical approach, assuming a power law of velocity distribution. The velocity and shear distribution was worked out mathematically for simple cases, and for more involved cases by a membrane analogy and the method of finite differences, as described in more detail in the following paragraphs.

An attempt was made to determine the distribution of shear or tractive force on the perimeter of canals from published data on the velocity distribution in trapezoidal channels. All available data on trapezoidal shapes (including the special cases of rectangular and triangular shapes) were used. Considerable data on rectangular and triangular shapes were available, but unfortunately there were very little on trapezoidal sections of the shape ordinarily used in earth canals. The method used was that first developed (or at least brought into the literature of the United States) by J. B. Leighly. 25/ Consider the cross section of a channel through which water is flowing, as shown in Figure 2. According to the principles of tractive force, the total tractive force on the perimeter for a unit length of canal is equal to the component of the weight in the direction of flow of the volume of water in this unit length of canal.

If sufficient measurements of velocity have been made at this section to show the velocity distribution, by drawing the isovels (lines of equal velocity) it is also possible to divide the cross section of the flowing water into a series of subareas by orthogonal lines or lines running perpendicular to the isovels and the perimeter of the canal, and ending in the point of maximum velocity. Since these lines are perpendicular to the lines of equal velocity, there is no velocity gradient across the lines, hence no net exchange of momentum across them and therefore no net shear. The tractive force due to the weight of the water enclosed between the lines originating from the bottom and sides of the canal is therefore exerted on that part of the bottom or sides between the respective lines. By planimetering these partial areas, and thus determining the volumes of water involved, it is possible to compute the tractive force exerted on each of the parts of the canal perimeter and thus establish the tractive force distribution over the bottom and sides. The disposition of the tractive force due to the volume of water lying above the locus of maximum velocities in the verticals is an uncertain matter, as the science of channel flow has not yet been sufficiently developed to explain it. The lines perpendicular to the isovels in this region extend to the water surface, indicating a transfer of shear to the air above the surface. There is good reason to believe, however, that only a small part of the shear represented by the area above the locus of maximum velocities would be exerted on the air above the water surface, and that it would probably be near the truth to neglect the force acting on the air entirely. In the studies, the tractive forces on the bottom due to the area below the locus of maximum velocities were increased by the ratio of the total area above this locus to the total area below the locus. This approximation, while leaving much to be desired, seemed to be the best that could be made with the present knowledge of the situation.

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25/ "Toward a Theory of the Morphologic Significance of Turbulence in the Flow of Water in Streams," J. B. Leighly, University of California Publications in Geography, Vol. 6, 1932, pp. 1-22.

The data available were not sufficiently exact nor of sufficient quantity to provide an adequate solution by this method. The results were scattered widely, and in the range of shapes in which canals ordinarily occur it was not possible to determine the shear distribution with sufficient certainty to justify its use.

## THE ANALYTICAL APPROACH TO SHEAR DISTRIBUTION

An attempt was made to work out the shear distribution by a mathematical process using the logarithmic distribution of Von Karman and the boundary layer theory, but this was not found to be practicable. It was found possible, however, to handle mathematical solutions for a velocity distribution in which the velocity is any power of the distance from the bottom. With such a relation it was possible to obtain velocity distributions closely approximating those observed in actual channels. For example, such a comparison is shown in Figure 3.

Mathematical solutions were worked out for rectangular channels with bed width-depth ratios of 2:1. The distribution for a bed width-depth ratio of 2:1 also gave the distribution of a 90° triangular channel. It was not found feasible to use mathematical solutions for the ordinary forms of trapezoidal channels, and it was therefore necessary to resort to a membrane analogy. In order to check the reliability of this device, solutions were also made on it of several of the forms solved by mathematical analysis. Solutions were also made for several cases by means of the method of finite differences, which were also checked by comparisons with the mathematical solution. Unfortunately, space is not available to give an adequate discussion of this study. Those who are interested in it are referred to the detailed report covering this work. 26/ The results of these studies of shear distribution are given in Table 1. In this table the tractive forces at the different points on the perimeter are given in terms of wSD. In terms of the maximum shears on the sides and bottom of the section, which are the values needed for canal design, the results are given in Figures 4 and 5. It is believed that the results of these studies give the most reliable information on shear distribution which is available at the present time. These results indicate that for trapezoidal channels of the shapes ordinarily used in canals, the maximum shear on the bottom would be close to the value wSD, and on the sides the maximum is close to 0.76 wSD.

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26/ "Sedimentation studies in open channels--Boundary shear and velocity distribution by membrane analogy, analytical and finite difference methods," Olsen and Florey, Bureau of Reclamation Laboratory Report No. Sp-34.

## LIMITING TRACTIVE FORCES FOR NONCOHESIVE MATERIALS

Probably the most important factor in the design of clear water canals in coarse noncohesive material is the limiting tractive force which the various types of materials will stand. Although the idea of tractive force or shear has been known for many years and has been an important concept in sediment transportation studies for a considerable period, it has been applied in this country only to a very limited extent in the design of canals. In Europe it appears to have been more commonly used, but no record was found of extensive studies of its application to canal design there. It was necessary, therefore, to obtain data on this point from all available sources and to supplement this as far as possible by further studies. The investigations, therefore, consisted of two parts: (1) a thorough search of all available literature with the collection and analysis of all pertinent information, and (2) hydraulic studies of conditions in canals to supplement the available data. The study of available literature has been completed, but to date the hydraulic studies in canals have been limited to investigations on the canals of the San Luis Valley in Colorado. Further work along this line is planned for the future.

### Results of Investigation of Available Literature on Limiting Tractive Force

The study of the literature to determine the limiting tractive force to be used in design consisted largely of analysis of laboratory studies of critical tractive forces and the transportation of coarse sediment by flowing water. In addition to the laboratory experiments, a number of formulas have been proposed by various engineers to express the results of their studies on the values of critical tractive force. A number of values have also been given based on field observation.

Space limitations prevent an extensive discussion of the results of this literature investigation, and only the results are presented herein. These results can best be presented in the form of diagrams, showing the relation between the size of the particle composing the noncohesive material and the critical tractive force necessary to cause motion.

Much of the available data were in the form of experiments to determine the quantity of sediment of various sizes moved under various tractive forces. In the original reports on many of these experiments the shear on the sides of the flume was ignored, but the available data have been assembled and corrected by Johnson 27/ and his data have therefore

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27/ "Laboratory Investigations on Bed Load Transportation and Bed Roughness," J. W. Johnson, Soil Conservation Service Bulletin SCS-TP-50, March 1943.

been used. To determine the limiting value of shear from these experiments, the shear values were plotted for the various quantities of sediment moved, and by extrapolation of the trend of these results to zero movement, the average critical values have been determined. These results are shown on Figure 6. The data usually did not fall in a line but rather in a band, and the limits of this band, when extrapolated to zero sediment discharge, are also indicated by vertical lines extending above and below the average values to the upper and lower limits, respectively, of these bands. On this and subsequent figures are also shown, for the purposes of comparison with the results of data on other graphs, a line representing the relation tractive force in Kg per $m^2$ = diameter in cm.

In the studies of Chang 28/ and O'Brien 29/ considerable data were given on the results of limiting shears which were apparently defined by zero transportation rates, although this information was not clearly indicated. These data are shown on Figure 7.

In some of the laboratory experiments, attempts were made to determine by visual observation the values of shear which would just start motion of the material on the bed. In some cases the initial movement of individual grains in the bed was used as the criterion, and in others a general movement of the bed material was used. The data of this type are summarized on Figure 8, the criterion used for initial movement in each case being indicated as shown.

A comparison of the formulas proposed by various engineers for limiting tractive force is given in Figure 9.

## SAN LUIS VALLEY DETERMINATIONS OF LIMITING TRACTIVE FORCES

To provide additional information on limiting tractive forces, for coarse, noncohesive material, observations were made on canals in the San Luis Valley of Colorado. Laboratory studies of critical tractive force have usually been performed with particles of a small size range, but canals in coarse, noncohesive material are usually constructed in a material containing a large range of sizes. The experiments in the San Luis Valley canals not only provided information from prototype canals, but also gave insight into the stability of canals built in graded materials.

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28/ "Laboratory Investigations of Flume Traction and Transportation," Y. L. Chang, Transactions ASCE, Vol. 104, 1939, p. 1246.

29/ "Transportation of Bed Load in Channels," M. P. O'Brien and B. D. Rindlaub, University of California, 1934.

The canals experimented upon are located where the Rio Grande leaves the mountains in Colorado and flows out onto an alluvial cone. The material composing this cone decreases in size from the apex outward, and provided canals in material of a wide range of sizes. The canals were stable, very straight and regular in section, and were steep enough to give high velocities and tractive forces. In general they furnished an unusually complete opportunity for experimentation.

It was expected that the water in flowing down these canals at high tractive forces would remove all of the material below a certain size and that this size would be indicated in the mechanical analysis of the material on the canal beds. This would be the size moved by the tractive force which had acted in these canals. However, this expectation was not realized, as the smaller particles were shielded by the larger ones and a critical size could not be determined.

The tractive forces acting in these canals were therefore compared with the composition of the material through which the canals were constructed, as determined by samples taken from borrow pits at the various sites. The size used in the comparison was that size of which 25 percent of the weight of the material was larger. The tractive force used was that resulting from the maximum sustained flow which had recently occurred in the canal, as nearly as could be determined from the flow records.

Fifteen reaches of canal were used, having discharges ranging from 45 to 1,500 second feet and slopes from 4.7 to 51 feet per mile. The results of the measurements are summarized in Figure 10, on which is plotted the tractive force determined from the sustained flow against the 25 percent greater size. On this graph is plotted a line representing the relation: tractive force in pounds per square foot = 1/2 the diameter in inches. This line represents practically the same relation as the line used in Figures 6 to 9, inclusive, differing only 4 percent from it. This difference is well within the limit of uncertainty of the data. The difference was introduced to obtain a simple relation in English units for use in design. The discussion of the results and their application to limiting tractive forces for design purposes will be taken up later in this report.

## THE EFFECT OF SIDE SLOPES ON LIMITING TRACTIVE FORCE

The effect of side slopes on limiting tractive force has been developed, by considering the forces acting on a particle on the sides of the canal, as previously pointed out. These forces are the force of the water, tending to move the particle down the canal in the direction of the flow, and the force of gravity, tending to move the particle down the sloping side of the canal. By combining these actions, the effect of the slope of the sides on the critical tractive force necessary to cause motion can be evaluated.

For convenience in design, the effect of side slopes was worked up into a factor, K, which is the ratio of the tractive force required to start motion on the sloping sides, to that required, in the same material, to start motion on a level surface.

This ratio involves only the angle of side slopes of the canal and the angle of repose of the material and is expressed by the following formula:

$$K = \cos \phi \sqrt{1 - \frac{\tan^2 \phi}{\tan^2 \theta}}$$

where

K = the ratio of the tractive force necessary to start motion on the sloping side of a canal, to that required to start motion for the same material on a level surface

$\theta$ = the angle (with the horizontal) of repose of the material

$\phi$ = the angle (with the horizontal) of the side slope of the canal.

The derivation of these equations is given in a report which is now in preparation. 30/

For convenience in solving this equation, Figure 11 has been prepared. For example, in a material whose angle of repose was 30°, the critical tractive force which would move material on the side of a canal with 2:1 side slopes would be 0.44 times that which would cause motion on a level surface.

## Studies of Angle of Repose of Noncohesive Material

As previously pointed out, the stability of the side slopes of a canal in noncohesive material involves the angle of repose of the material. A study was therefore made of this subject, beginning with a thorough review of all available literature on it. This was followed by a limited amount of laboratory investigations and observations on a large number of stock piles of various-size material at gravel washing plants.

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30/ "Critical Tractive Forces on Channel Side Slopes," (revised edition), A. C. Carter and E. J. Carlson, Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-295.

When the digest of literature was undertaken, it was thought that it was necessary to establish the angle of repose of all noncohesive material, and literature on all sizes of materials was therefore included. As the study progressed, it became evident that in channels carrying water in finer materials the cohesive forces, even with comparatively clear water, become so great in proportion to the rolling down forces that the latter can safely be neglected, and therefore only the angles of repose of the coarser materials need be studied. The most important results of the study of the literature for this class of material are summarized in Table 2.

The results of the studies made in the laboratory are given in Figure 12. The experiments showed that a considerable range of values could be obtained in repetitive tests, but time was not available to make a sufficient number of observations to obtain accurate average values, and the determinations made, therefore, are subject to considerable scatter. The results showed that for the larger sizes, the angles were not materially different for the various conditions of stacking in air or water, but for the sand sizes these had more effect. The average results of all observations of the angle of repose of stock piles at gravel-washing plants are also given on this figure.

Although these data indicate that the angle of repose increases with both size and angularity, the data scatter widely and are insufficient in number to closely determine any quantitative relations.

For use in design, Figure 13 was drawn up, giving values of the angle of repose for material above 0.2 inch in diameter for various degrees of roundness. In this diagram the angles of repose have been somewhat arbitrarily limited to a maximum value for very angular material of 41° and very rounded material of 39°. This was believed necessary to secure conservative designs because of the lack of data on angles of repose of the larger size material.

## HYDRAULIC ROUGHNESS OF CANALS IN NONCOHESIVE MATERIAL

Measurements of flow of water in channels have demonstrated that the hydraulic roughness of canals in coarse, noncohesive material changes appreciably with the size of material involved. In designing canals in such material, it is therefore important that this be considered if correct predictions of the canal discharge capacity are to be obtained. It is equally important that the slopes be accurately estimated if reliable values are to be obtained of the tractive force which will act on the sides and bottom of the channel. In order to secure more reliable design of stable channels in such material, a study was therefore made of the relation of hydraulic roughness to particle size of canal material. The first step in this study consisted of a review of all available literature on this subject. The data from the experiments carried out by this Bureau on the flow in the canals of the San Luis Valley were also included. These studies showed that the hydraulic roughness of canals, as expressed by the roughness factor "n" in the Manning formula, increases as the size of the material becomes larger. There is reason to believe, from the results of measurements of flow in pipes, that if adequate data were available, it would be possible to work out a roughness relation based on the ratio of the particle size to the hydraulic radius, which would be more exact than one based only on size. There is also evidence that the hydraulic roughness depends largely on the extent to which the actual cross-section shape departs from the plane surfaces for the bottom and sides shown on the canal design drawings. The data available were not sufficiently extensive, nor in enough detail, to differentiate between these influences, and relations including them, therefore, could not be worked out.

The results of the San Luis Valley tests scattered somewhat, but the average could be represented by the equation:

$$n = \frac{d^{1/6}}{41}$$

where n is the Manning's n, d is the median diameter in inches of the particles composing the bed. This value of n is somewhat larger than the value $n = d^{1/6}/44.4$ obtained by Strickler. 31/ It should be noted that the median size of the material on the bed was considerably larger than that of the material through which the canal was constructed, due to the washing out of the fine material from between the larger particles. In designing a canal it will therefore be necessary to estimate what the bed composition will be after the fine material has been washed out by the flowing water. As the value of n increases with the 1/6 power of the diameter, high accuracy in determining the diameter is not necessary. The canal sections from which these roughness values were obtained were especially uniform, and for design purposes the roughness in the Manning formula indicated by the relation developed from the San Luis Valley tests probably should be increased by about 15 percent. The equation developed is only applicable to coarse, noncohesive material.

## DETERMINATION OF LIMITING TRACTIVE FORCES FROM LIMITING VELOCITIES

The data for critical tractive forces obtained from laboratory experiments are applicable to the case of coarse, noncohesive material, but experience has shown that canals can stand materially higher values

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31/ Bertrage zur Frage der Geschwindigeckformal und der Rahigkeitszahl fur Strom Kanale und geschlassen Leitungen, Mitt. No. 16 des Eidg. Amtes fur Wasserwirtshaft, Bern., 1923, K. Strickler.

of tractive force than that which would just start movement in fine, noncohesive material. For the design of canals in this material, therefore, something more than determinations from laboratory studies is necessary. No laboratory data are available for limiting tractive forces in cohesive material. For both of these cases it would be very desirable if limiting tractive forces could be determined from observations on actual canals. Although study along these lines for Bureau of Reclamation canals is underway, sufficient information for this purpose has not yet been accumulated.

Until field studies of canals in fine, noncohesive and cohesive materials can be made using the tractive force principle, the only method of determining limiting tractive force values for such canals is from the limiting velocities which these canals will stand. A great deal of information on such velocities has been accumulated. Since velocity is not a completely rational parameter for determining scour, these velocity data are not entirely satisfactory, but by an intelligent utilization of it valuable information can be obtained for use in scour analysis by the tractive force method. An attempt has therefore been made to analyze the data on permissible velocities in canals, as presented in the available publications, and to determine from the values of limiting velocities given the values of tractive force which they represent.

The three sources of systematic data on permissible velocities in canals which will be safe against scour which are available are those of Etcheverry, Fortier, and Scobey, 21/ and the USSR data on Tables 5-8. The data given by Etcheverry (Table 3) are not related by him to the size of canal. The data by Fortier and Scobey are given in Table 4. They state that the values given are for "a depth of 3 feet or less," and suggest that for greater depths a mean velocity greater by 0.5 foot per second may be allowed. They also state that the values are applicable to canals "with long tangents predominating throughout their length," that for canals in sinuous alignment a reduction of about 25 percent is recommended. These values are for canals which have been "aged," or brought up to capacity gradually over a considerable period. This table also gives values which Fortier and Scobey recommended for use when the water transports colloidal silts.

The USSR data give the permissible values for granular material of various diameters, as shown on Table 5. These values are for a mean depth of 1 meter, and for water carrying less than 0.1 percent of sediment of less than 0.005-mm size. For other mean depths these values can be multiplied by factors as shown in Table 6. The article also states that the permissible velocities of Table 5 can be raised by the following percents for flows containing 0.1 to 2.5 percent of sediment less than 0.005-mm diameter; sand 25-65 percent; gravel 10-45 percent; pebbles 0-25 percent. For cohesive material the values given for 1 meter mean depth are as shown in Table 7, and the corrections for other depths are given in Table 8.

To convert the values of limiting velocity given in the three articles previously discussed into exactly equivalent values of tractive force, it is necessary to know the size, shape, shear distribution, and energy gradient of the channels to which these values apply. Since these data are not given in the articles, it is necessary to make certain assumptions regarding them. In the following paragraphs, the assumptions used in converting the various values of limiting velocity are discussed.

Fortier and Scobey realized that greater depths permitted higher velocities and therefore specified the depths to which their velocity applied as 3 feet or less. If the tractive force analysis is sound, a single velocity could not apply to a range of depth from 3 feet to zero. It is believed that most of the canals from which the limiting velocity data were derived had depths in the neighborhood of 3 feet, and this depth has therefore been used in the conversion. If the tractive force principle is correct, the value for a 3-foot depth would vary with the width of the canal and the side slopes. For this conversion, a bottom width of 10 feet and side slopes of 1-1/2:1 have been used, as these were believed to represent as closely as can be estimated a mean of the most probable condition of the canals on which the data were obtained. The energy slope of the canals must also be used, and to determine it what was believed to be the most probable value of hydraulic roughness for the nature of the material in which the canal was located was used, with the Manning flow formula. Much of the uncertainty of using values of tractive force obtained in this manner is eliminated if the same values of roughness and formula are used in computing the energy gradient for the canals under study as were used in determining the permissible tractive forces from the permissible velocities. The values of hydraulic roughness used in arriving at the tractive forces are therefore noted. The values of tractive force corresponding to the Fortier and Scobey values of limiting velocity, as computed under these assumptions, are also given in Table 4. Since the use of a single tractive force value provides in a rational manner a larger velocity for greater depths, no attempt was made to consider the less rational Fortier and Scobey correction for greater depths.

Since the Etcheverry data included no information on size, shape, or side slope of the channels, the same assumptions were made somewhat arbitrarily in converting it as were made in the case of the Fortier and Scobey data. The values of tractive force corresponding to the limiting velocities given by Etcheverry are also given in Table 3.

The permissible velocities of the USSR data are for an average depth of 1 meter. These have been converted into tractive forces assuming the same bed width-depth ratio as assumed for the data from other authorities. Their corrections for other depths are such that practically the same values of tractive force would be obtained if these other depths of flow had been used in estimating the equivalent tractive forces.

## THREE CLASSES OF MATERIAL IN WHICH CANALS ARE CONSTRUCTED

In designing canals that will be free from scour while carrying relatively clear water, one of the most important factors is the material through which the canal passes. These materials fall into three classes, each of which requires a different method of analysis. These three classes are: (1) coarse, noncohesive material, (2) fine, noncohesive material, and (3) cohesive material.

For the design of canals in coarse, noncohesive material, one must consider not only the limiting tractive force on the bottom but also the action of the particles in rolling down the sloping canal sides. This requires an analysis of the combination of the rolling effect with the longitudinal force of the flowing water, as previously pointed out, and involves the angle of repose of the material. The distribution of the tractive forces on the perimeter of the canal must also be considered. Since the hydraulic roughness of canals in this class varies widely with the size of the particles of the material involved, the roughness factor also is important.

Where the canal is constructed in cohesive material, the particles are prevented from rolling down by cohesion, and hence, the rolling down part of the analysis is not applicable. The design, therefore, involves only the distribution of the tractive force for material in which the canal is constructed. In these canals the hydraulic roughness is not a function of the particle size but rather of the surface irregularities.

Canals in fine, noncohesive material are intermediate between the other two classes. In this class the effect of small amounts of cohesive sediment in the water or in the material through which the canal flows becomes important.

### Limiting Tractive Forces in Canals in Coarse, Noncohesive Material

The material for determining the limiting value of tractive force for use in design of channels in coarse, noncohesive materials consists of the data obtained from the San Luis Valley canals and the results of the determinations of limiting tractive force obtained by computation from limiting velocities, as given by Etcheverry, Fortier, and Scobey, Nuernberg Kulturamt, and the USSR article. Of these, the studies made on the San Luis Valley canals are most detailed and complete. These latter results are shown on Figure 10. The line A on this figure represents the relation: tractive force in pounds per square foot equals 1/2 the diameter in inches of a particle such that 25 percent of the material in which the canals were constructed is coarser. This line has practically the same value as the reference line given on Figures 6, 7, 8, and 9.

Since most of the observations fall either above or very close to this line, it is believed that it probably represents very nearly the true value for limiting tractive force in canals in such material. It is believed, however, that it does not contain sufficient factor of safety for use in design and a value of limiting tractive force in pounds per square foot equal to 0.4 the diameter in inches for the size for which 25 percent of the materials is larger as shown by line B is therefore tentatively recommended for design.

For metric units a similar relation can be used. It is: the tractive force in kilograms per square meter is equal to 0.8 the size in centimeters. This relation differs only 4 percent from the one given in English units.

As these relations were determined on straight canals, its use should be limited to such conditions. For curved canals lower values of tractive force should be used.

The justification of using a direct relation between the diameter of the 25-percent larger size and the tractive force is believed to be amply justified by the evidence on Figures 6, 7, and 8, which show that the general trend of all the data obtained is close to this relation; also, that this relation is used by nearly all of the formulae proposed, as shown by Figure 9. In addition, it is indicated by the commonly used relation that the velocities necessary to move particles vary very nearly as the square root of the particle diameter, and tractive forces vary with square of the velocity.

In canals designed with this relation, some of the finer material on the banks and bed when first constructed would be moved downstream, uncovering coarser particles which would protect the bed and banks. If this movement is likely to produce undesirable effects, measures to meet this situation will be required. For example, this material moving down a power canal might erode the machinery, and steps to prevent it would be necessary till all the material was moved out and stability was attained.

The results based on Etcheverry and Fortier and Scobey's limiting velocities are inexact, because of the difficulty of accurately delineating the type of materials by the general terms used in their classifications. The relation determined from the San Luis Valley observations is generally somewhat smaller than that shown by the USSR data and somewhat larger than that indicated by the Nuernberg Kulturamt data as shown on Figure 14. It is believed, therefore, that it represents a safe basis for design.

For the design of canals, it is necessary to combine the relations shown by the line on Figure 10 with the effect of the side slopes and of the tractive force distribution on the perimeter of the canal. The method of effecting this combination can best be presented in the form of an example. Suppose that a canal is proposed through slightly angular material, 25 percent of which is 1 inch or over in diameter, and that the canal water section has a 10-foot bottom width, 5-foot depth, and side slopes 2:1. The ratio of bed width-depth is therefore 2. The maximum tractive force on the bottom for a trapezoid with $B/D = 2$ and 2:1 side slopes is shown by Figure 5 to be $0.89wDS$. No motion will occur on the bottom if this $0.89wDS$ does not exceed the limiting value for the material in which the canal is constructed. This limiting tractive force value for material, 25 percent of which is over 1 inch in diameter, is shown by Figure 10 to be 0.40 pound per square foot. The limiting longitudinal slope for the canal is, therefore, $S = 0.40 \div 0.89wD$, where $w = 62.5$ lb/cu ft and $D = 5$ feet. This limiting slope for movement on the bottom is therefore 0.00144.

To be stable on the sides of the channel the limiting tractive forces must be less than would be safe on a level bottom, by an amount which depends on the side slope of the canal and the angle of repose of the material. The safe angle of repose of slightly angular material of 1-inch diameter is shown by Figure 13 to be 36°. For side slopes of 2:1 and an angle of repose of 36°, Figure 11 shows that the safe tractive force on the side slope would be 0.64 of that on a level bottom, or for this case $0.64 \times 0.40 = 0.26$ lb/sq ft. The maximum tractive force on the sides of a trapezoid with $B/D = 2$ and side slopes 2:1 is shown by Figure 4 to be $0.76wDS$. The longitudinal canal slope required to produce the limiting tractive force on the sides is, therefore, $S = 0.26/0.76wD = 0.00108$. Since this limiting longitudinal slope is smaller for the sides than for the bottom, the former would control and the canal should not be built with a slope of more than 0.00108.

## Limiting Tractive Forces for Canals in Fine, Noncohesive Material

Based on a consideration of all of the available data, it is believed that the best recommendation which can be made at this time for canals constructed in fine, noncohesive material are those given in Table 9. The comparison of these with most of the data available is shown in Figure 14.

The tentatively recommended values for clear water were selected largely to agree with the Fortier and Scobey value, and conform to the general trend. They are somewhat higher than the USSR values for clear water. The curve of the latter contains a peculiar break of curvature at the 1.0-mm size, but no explanation of this was given in the article. The values recommended are slightly above the Straub values of critical tractive force, which were based on laboratory and stream observations.

The values of limiting tractive force tentatively recommended for canals carrying water containing a high content of fine sediment are considerably higher than for clear water, and are based largely on

Fortier and Scobey's value for canals in fine sand carrying colloidal silts but they also conform well with Schoklitsch's value for canals in sand. Since "high content of fine sediment" would be interpreted differently by each person, depending on his experience, it is desirable to define this more closely. For high content of fine sediment the author had in mind water streams that would contain a load of 2 percent or more of silt and clay sizes, on an average of two or three times a year, but would carry only a low content of sand. Unfortunately, sufficient information is not available to set limits for the allowable sand content. Where much sand is carried, this method of analysis is not applicable.

Since these data were largely obtained from limiting velocities for straight canals, the values recommended are also for such alignment.

The tentatively recommended values for canals carrying a low content of fine sediment in the water are intermediate between the case of clear water and that of heavy sediment load. It conforms in general with the values given by the Nuernberg Kulturamt (N.K.). By low content of fine sediment, the author has in mind a content of silt and clay sizes reaching about 0.2 percent on the average two or three times a year. The sand content should be very low.

It will be noted that the values tentatively recommended for clear water are very much higher for the fine sand than the critical tractive forces indicated from flume tests. The general order of magnitude of the values in the two cases appears to be well established and some explanation of the difference is therefore needed. This difference is probably due to the fact that clear water such as is used in the laboratory is seldom obtained in natural channels, and the sand through which the canals pass is rarely as clean as that used in the laboratory, but usually has at least a little binder material in it. The growth of minute organisms in the water may also be a factor. Another factor is that a slight movement of material in a canal would not cause it to be considered unstable, as it would probably not have objectionable results.

The higher values allowable with fine suspended sediment are probably largely due to the cementing effect of this material on the banks and bed of the channel. In the case of high fine sediment content it is probably partly due also to the fact that with a silt and clay size content of 2 percent, some sand would be carried, and this would reduce the effect of the scour on the bed.

The size specified for the fine, noncohesive material is the median size, or size of which 50 percent of the weight is larger, while the size specified for the coarse, noncohesive material is the size of which 25 percent is larger. The median size is used for the fine material because this is the usual criterion for describing such material. In the coarse material only the coarser material remains to protect the bed and banks, and the 25-percent larger size defines this large material much better than the median size. The use of the two systems introduces an uncertainty in the vicinity of the 5-mm size, which was somewhat arbitrarily selected as the division between these classifications. For example, a material in which the part larger than 5-mm size falls between 25 and 50 percent would be included in both the coarse and fine classification. It is believed, however, that this difficulty can be removed by using whichever classification gives the lower tractive force.

### Limiting Tractive Forces in Cohesive Materials

For the design of canals in cohesive material the only data on safe tractive forces available are those obtained by converting limiting velocities as given by Etcheverry, Fortier and Scobey, and the USSR data to the values of tractive force. Studies are underway to evaluate the experience with the canals of the Bureau of Reclamation projects, from which it is hoped more complete information can be obtained, but to date a digest and synthesis of the available material into a systematic procedure has not been accomplished. Until this is done, canal designers wishing to use tractive forces in their designs will have to select limiting values of tractive force from an examination of the data based on the conversion of limiting velocities to tractive force given in Tables 3, 4, and 7.

In canals in cohesive material the effect of the distribution of tractive forces, as shown in Figures 4 and 5, should be considered, but the rolling-down effect is not applicable.

## EFFECTS OF BENDS

Perhaps the phase of stable channel design regarding which least is known is the effect of bends. It has long been evident that sinuous canals scoured more easily than straight ones, but almost nothing of a quantitative nature is available on this effect. A study of the scour at bends, both in the laboratory and in the field, is a part of the program of stable channel studies being carried on by the Bureau of Reclamation.

Canals of the Bureau of Reclamation have sometimes been designed to limit the radius of bends to six times the water surface width. On other canals a limit of 15 times the water depth has been used. There is great need, however, of more accurate knowledge on which to base design procedures.

The scour in bends can be reduced by lowering the velocity of flow, which may be accomplished by using larger canal areas, but this results in an increased cost. It will often be more economical to allow scour to start in canals and stop it by protecting the banks at the points where scour occurs, rather than use the larger cross sections necessary to insure that no scour will take place. With the present knowledge, it is impracticable to place protection at the bend in advance as this would lead in many cases to protection where it was not needed.

It is hoped that the publication of this progress report will bring out some discussion on the effect of bends. Since this experience is likely to be in terms of velocity, however, it will be necessary to convert it into tractive force. Data will be more easily compared if some basis of comparison is given. For this purpose the comparison of the velocities and tractive forces in straight canals and canals of different degrees of sinuosity can be used. In order to define more closely the meaning of these various degrees of sinuosity, the following may be useful: Straight canals have straight or very slightly curved alignment, such as are typical of canals in flat plains. Slightly sinuous canals have a degree of curvature which is typical of slightly undulating topography. Moderately sinuous canals have a degree of sinuosity which is typical of moderately rolling topography, and very sinuous canals have a condition of curvature which is typical of canals in foothills or mountainous topography. It will be seen that the tractive force values have a wider range than the corresponding mean velocities. These values are, in the writer's opinion, as close to the true values as it is possible to come, at the present time, with the data available to him. Because the values are based so largely on judgment, however, rather than observed data, one does not feel justified in making them as a recommendation.

## NONSCOURING CANALS OF MINIMUM EXCAVATION AND WIDTH

In studying trapezoidal canals, considering the distribution of tractive force on the sides and bottom and the rolling-down action of the material on the sides, as pointed out previously in this paper, it was found that the tractive forces close to the limiting value occurred over only a part of the perimeter of the canal, and on most of the perimeter forces less than this amount acted. It was believed that a section on which the limiting tractive force acted over the entire perimeter might have interesting properties, and the mathematical requirements of such a section were therefore set up and its shape determined. Study showed that within the limitations of the approximating assumptions used, this section had other important properties, in addition to the property of impending motion over the entire periphery, which, under certain conditions, might make possible substantial savings. Further studies were therefore made to refine the accuracy of the determination. In the following paragraphs, the principal results of this study are given.

The section developed, in which the material on the entire wetted perimeter is in a state of incipient motion, and the side slopes above the water line are at the angle of repose was found to have also the following interesting properties: for a channel in a coarse, non-cohesive material of given angle of repose and given discharge, this section provides not only the channel of minimum excavation where the water surface is below the ground level, but also the channel of minimum top width, maximum mean velocity, and minimum water area for these conditions.

The shape of the channel is dictated by the following five assumptions: (1) at and above the water surface, the side slope is at the angle of repose of the material; (2) at points between the center and edge of the channel the particles are in a state of incipient motion, under the action of the resultant of the gravity component of the particles submerged weight acting down the side slope and the tractive force of the flowing water; (3) at the center of the channel the side slope is zero and the tractive force alone is sufficient to cause incipient motion; (4) the particle is held against the bed by the component of the submerged weight of the particle acting normal to the bed; and (5) the tractive force on any area is equal to the component of the weight of the water above the area in the direction of flow. Under assumptions 1, 2, and 3 the particles on the entire perimeter of the canal cross section are in a state of impending motion.

For the fifth assumption to be true, there can be no transfer of force horizontally between adjacent currents moving at different velocities in the section. This is, of course, not the case, as the faster moving water near the center of the channel tends to carry along the slower moving water near the sides. As part of this study, however, a detailed mathematical treatment of this problem was carried out, which indicated that for the shape of channel which would be likely to be encountered in practice, the departure of the approximate assumption from the true conditions would have very little effect on the shape of the section.

The development of the form of this channel has been described in a separate report 32/ and will not be given here. For a given discharge and longitudinal canal slope in a material of given angle of repose and having a known limiting tractive force, the solution gives the shape and dimensions of the channel which will have the properties previously discussed.

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32/ "Stable Channel Profiles," R. E. Glover and Q. L. Florey, Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-325.

The belief that this section has the properties stated is based on the following reasoning: Since the slope of the section at the water's edge is at the angle of repose, at this point the material is in a state of incipient motion. Consider a unit length of the canal in which water is flowing, divided into sections by vertical planes in the direction of flow. In the cross section determined by this analysis, the bottom at all points is in a state of impending motion. Beginning with the section at the bank, if the side slope beneath it were steepened, motion of the particles on the bed would occur, because of both the increased angle of side slope, and the greater tractive force resulting from the greater depth. This condition also holds for all of the other sections. The side slope of the bottom at all sections is, therefore, the maximum for stability and the depth of any section also a maximum. Since the depth of all sections is a maximum, the hydraulic radius of each is a maximum and, therefore, the velocity through each section is a maximum. The mean velocity of the entire section, therefore, must also be a maximum. Since the mean velocity in the water section is a maximum for a given discharge, the water area must be a minimum. Since the depth of each section is a maximum and the water area is a minimum, the surface width also must be a minimum. If the surface width is a minimum and the side slopes above the water line are at the angle of repose, which is the steepest slope with stability, the cross section of excavation above the water line is the smallest possible with stability. Since the water area is also a minimum, the total cross-sectional area and the total excavation is likewise a minimum.

Most hydraulic engineers have been taught the proposition that the shape of an open channel with minimum area for a given discharge is semicircular, since this is demonstrated in most textbooks of elementary hydraulics. Many books also develop the shape of trapezoidal channels of various side slopes which give the minimum area for a given discharge. A point that is never brought out in the books is that these are channels of minimum water cross-sectional area, and not necessarily channels of minimum excavation. They are channels of minimum excavation only if the ground surface coincides with the water surface. Where the water surface is below the ground surface, as is frequently the case, canals narrower than those indicated by the relations developed give minimum excavation, and when the water surface is above ground level, wider canals give minimum excavation. The semicircular cross section is impracticable for unlined canals in earth, since it has sides approaching the vertical which would, in most cases, not be stable, even in coherent material.

A trapezoidal canal designed on these textbook principles for coarse, noncohesive material, if stable, would require more excavation, greater width, have greater water area, and lower mean velocity than the section of incipient motion over the entire perimeter herein developed.

As this form of channel is in a state of incipient motion, both above and below the water line, it will often not be desirable to use it directly in design without a factor of safety. It is possible to introduce a factor of safety which will apply both to the bed and the banks, so that on the entire periphery the factor of safety is the same. If desired, different factors of safety can be used above and below the water line.

A channel having the same factor of safety, F, against motion at all points on the perimeter can be secured by designing the channel as if (1) the angle of repose was $\Theta'$ where $\tan \Theta' = \tan \Theta/F$ ($\Theta$ being the true angle of repose of the material) and (2) as if the limiting tractive force was $T'$ where $T' = T/F$, T being the true limiting tractive force of the material on a horizontal bottom.

Although the analysis described herein was developed entirely by the forces of the Bureau of Reclamation, after it was accomplished it was discovered that a similar analysis of a section in which the material on the entire perimeter was in a state of impending motion was previously developed by Chia-hwa Fan 33/ on the basis of the author's analysis of the rolling effect, 23/ and Mr. Fan is therefore entitled to priority credit for this part of the analysis. Mr. Fan, however, apparently did not realize the fact that these sections provided the minimum excavation, width, and water area and maximum mean velocity, nor the possibility of introducing factors of safety. His solution fixes the longitudinal slope which must be used, but does not provide for cases using other slopes, as does the solution given by this study. Since the assumptions he used are slightly less exact than those used herein, it is believed that the latter give somewhat more exact results.

## FUTURE STUDIES

The program of studies undertaken by the Bureau of Reclamation for the improvement in canal design procedures is well underway but a great deal of work remains before its completion.

The following studies should be carried on: Additional studies of limiting tractive forces are needed along four lines: (1) laboratory tests of graded materials, to study the shingling effect of the removal of the finer fractions of a graded material, to determine safe values of design for such mixtures of sizes and the amount of material moved away

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33/ "A Study of Stable Channel Cross Section," Chia-hwa Fan, Hydraulic Engineering (published by the Chinese Society of Hydraulic Engineers), Vol. 15, p. 47.

before stability is obtained. A study of the effect of the shape of the particles on the critical tractive force should also be made. (2) Studies of available data in the literature and field observations to obtain better knowledge of the limiting shear on cohesive material and on the material formed by the deposit of fine sediment carried in suspension by the canals. (3) A field study of the experience with scour in Bureau of Reclamation canals, when expressed in terms of tractive force; and (4) A study of the scour resistance of clay soil and its relation to the properties of clay involved in its structural stability.

Further studies of shear distribution are also desirable, composed of both laboratory and field investigation. The laboratory work should consist of measurements of shear distribution on the periphery of trapezoidal channels and the corresponding velocity distribution, for channels both of equal and unequal roughness on the sides and bottom. Field studies of velocity distribution in similar channels would also be made to compare with the laboratory studies and thus obtain correlation of model and prototype shear distribution.

Model studies of trapezoidal channels on coarse material should be carried on to establish the degree of reliability of the analysis of the rolling-down effect on the side slopes developed in this report. Further studies should be made of the angle of repose of material of different sizes, shapes, and also on graded material of various sizes. Particularly, attention should be given to the larger sizes of material to allow for removal of the arbitrary limitations suggested in this report.

Laboratory and field studies of the laws of sediment transportation should also be carried on to determine better methods of estimating the quantity of various sizes of sediment carried by canals. Work along this line is now in progress under the Hydrology Branch of the Bureau.

A study should be undertaken to try to correlate and compare the canal-analysis methods developed in India and Pakistan with the methods developed in this paper in order to obtain any advantages there might be from a combination of the methods or data.

The question of the effect of bends should be studied, both in the laboratory and in the field. The laboratory study should consist of experiments with bends of various radii, central angle, bottom width, side slopes, and velocities to study the scouring effects under various conditions. The possibilities of spiraling curves and superelevation of the bed should also be considered. The field study should consist of observations on bends in canals which have produced scour, to obtain data on the conditions which cause trouble in actual cases.

A laboratory study should also be made to establish the degree of reliability of the analysis of the shape of the channel of impending motion throughout the sides and bottom.

## SUMMARY

The methods of design suggested in this report are based on the results of the studies described herein and are largely the author's interpretation of those results. Since they have very recently been completed, they do not represent experience based on a long period of use in canal design. Time has not been available to secure a thorough discussion of them from the many qualified persons in the Bureau of Reclamation, and no formal action on them by the Bureau has been taken, although the general reaction to these suggestions seems to be favorable and the use of tractive force by Bureau personnel in place of velocity as a parameter of design is rapidly spreading. Some of the processes seem to be well established, and others, because of lack of data, are based on less well-established foundations. In all cases, the author has attempted to indicate so far as space limitations permitted the extent of the supporting information. The need of further studies to check and perfect the methods proposed herein is evident and this paper should be considered, therefore, to be of the nature of a progress report. It is the author's belief, however, that the results described and the methods proposed herein represent progress toward better stable channel design, and that their use for design in their present form is amply justified until further studies can be made to perfect them.

## ACKNOWLEDGMENTS

The studies described in this paper were the work of a large group of men on the staff of L. N. McClellan, the Chief Engineer of the Bureau of Reclamation. The number who have taken part in these studies is so large that it is practicable to acknowledge only those who made the more important contributions to it.

Most of the mathematical work of this study, including that on the analysis of the most efficient channel and the shear distribution on the perimeter of canals, was carried on by R. E. Glover, Research Engineer, assisted by F. E. Swain, R. G. Conard, and Q. L. Florey. The membrane analogy studies were carried out by O. J. Olsen under the direction of D. McHenry, who also introduced the method of finite difference analysis. A. C. Carter carried on the studies of shear distribution in canals based on velocity distribution, on limiting tractive forces, angles of repose, and effect of side slopes. O. S. Hanson investigated the hydraulic roughness of canals and angles of repose. E. J. Carlson carried on most of the studies of the San Luis Canal data, and also studied hydraulic roughness, angles of repose, and effect of side slopes. C. R. Miller also worked on the San Luis Valley canal studies. R. P. Verma assisted on the velocity distribution studies. These investigations were largely carried on as a part of the work of the Hydraulic Laboratory Section, which is directed by H. M. Martin with C. W. Thomas in charge of this part of the work. The staff of the San Luis Valley Project office carried on the canal measurements in that valley. Helpful advise was also received from R. E. Glover, D. J. Hebert, C. R. Burky, I. B. Hosig, P. W. Terrell, H. G. Curtis, and N. L. Govinda Rao.

Table 1

**TRACTIVE FORCE DISTRIBUTION IN TRAPEZOIDAL CHANNELS**
**In terms of wSD****

| Method | | Membrane analogy | | | | | | | | | | | | Analytical | Finite difference | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shape of channel | | Trapezoidal | | | | | | V-notch | | | | | Rectangular | | | | |
| Side slope ss | | 2:1 | 2:1 | 2:1 | 1-1/2:1 | 1-1/2:1 | 1-1/2:1 | 2:1 | 1-1/2:1 | 1:1 | 2/3:1 | 1/2:1 | 0:1 | 0:1 | 0:1 | 0:1 | 0:1 |
| Bottom width b | | 2 | 4 | 8 | 2 | 4 | 8 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 4 | 1 |
| Side boundary points, vertical distance above bottom | 1.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | *0.680 | *0.686 | *0.686 | *0.744 | *0.468 |
| | 0.9 | 0.130 | 0.130 | 0.120 | 0.160 | 0.190 | 0.160 | 0.130 | 0.160 | 0.230 | 0.270 | 0.275 | | .677 | .676 | .740 | |
| | 0.8 | .250 | .260 | .240 | .320 | .330 | .300 | .260 | .290 | .350 | .350 | .320 | .660 | .654 | .664 | .724 | .460 |
| | 0.7 | .380 | .380 | .360 | .450 | .450 | .420 | .380 | .400 | .440 | *.375 | *.325 | | .625 | .636 | .700 | |
| | 0.6 | .500 | .490 | .470 | .550 | .570 | .530 | .470 | .480 | .470 | .370 | .305 | .620 | .597 | .610 | .664 | .435 |
| | 0.5 | .600 | .590 | .580 | .620 | .650 | .610 | .550 | .530 | *.480 | .350 | .275 | | .566 | .560 | .610 | .415 |
| | 0.4 | .680 | .680 | .660 | .690 | .710 | .690 | .610 | .560 | .470 | .320 | .235 | .500 | .523 | .510 | .550 | .385 |
| | 0.3 | .730 | .740 | .730 | .730 | *.750 | .740 | *.650 | *.565 | .440 | .270 | .190 | | .449 | .436 | .476 | .342 |
| | 0.2 | *.760 | *.770 | *.770 | *.735 | .740 | *.760 | .640 | .520 | .350 | .190 | .130 | .320 | .335 | .340 | .360 | .278 |
| | 0.15 | .760 | .765 | .760 | .720 | .710 | .710 | .600 | .480 | | | | | | | | .235 |
| | 0.1 | .740 | .750 | .720 | .670 | .670 | .630 | .550 | .400 | .230 | .110 | .065 | .180 | .180 | .200 | .220 | .180 |
| | 0.05 | .670 | .660 | .640 | .530 | .590 | .520 | .440 | .290 | .130 | | | .100 | | | | .110 |
| | 0.025 | | | | | | | | | .070 | | | .060 | | | | |
| Bottom boundary points horizontal distance from outside edge toward center | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0.025 | | | | | | | | | | | | .060 | | | | |
| | 0.05 | | | | | | | | | | | | .100 | | | | .110 |
| | 0.1 | .700 | .730 | .720 | .660 | .640 | .660 | | | | | | .180 | .211 | .200 | .220 | .180 |
| | 0.2 | .770 | .800 | .770 | .730 | .740 | .730 | | | | | | .320 | .345 | .340 | .360 | .275 |
| | 0.3 | .800 | .840 | .810 | .780 | .790 | .780 | | | | | | | .436 | .436 | .470 | .332 |
| | 0.4 | .830 | .870 | .840 | .810 | .830 | .820 | | | | | | .500 | .507 | .510 | .556 | .362 |
| | 0.5 | | | | | | | | | | | | | .563 | .560 | .624 | *.372 |
| | 0.6 | .870 | | | .850 | | | | | | | | .620 | .605 | .610 | .684 | |
| | 0.8 | | .930 | .920 | | .910 | .910 | | | | | | .660 | .658 | .664 | .770 | |
| | 1.0 | *.890 | | | *.890 | | | | | | | | *.680 | *.675 | *.686 | .830 | |
| | 1.2 | | .950 | | | .950 | | | | | | | | | | .870 | |
| | 1.6 | | .960 | .970 | | .965 | .960 | | | | | | | | | .920 | |
| | 2.0 | | *.970 | | | *.970 | | | | | | | | | | *.936 | |
| | 2.4 | | | .980 | | | .980 | | | | | | | | | | |
| | 4.0 | | | *.990 | | | *.990 | | | | | | | | | | |

*Maximum values, bottom and side.

**w = unit weight of water
S = energy gradient
D = depth of flow

Table 2

ANGLE OF REPOSE OF COARSE, NONCOHESIVE MATERIAL
AS GIVEN IN LITERATURE

| Material | Angle of repose | Authority | Remarks |
|---|---|---|---|
| Gravel | 35° | Anderson | 34-percent voids |
| Gravel | 30°-48° | American Civil Engineers | Round to angular |
| Gravel | 39°-48° | Pocket book, Rankine's Applied Mechanics | |
| Gravel or soil | 37° | Massey | Dry |
| Cobbles | 39° | Massey | Dry |
| Gravel | 31° | Paaswell | |
| Shingle and gravel | 35°-48° | Trautwine | |
| Dense sand and gravel | 34° | Plummer and Dore | |
| Gravel | 30°-48° | Urquhart | Round to angular |
| Gravel 1/2 inch | 25° | Goodrich | |
| Gravel 1/4 inch | 19° | Goodrich | |

Table 3

COMPARISON OF ETCHEVERRY'S MAXIMUM ALLOWABLE VELOCITIES AND TRACTIVE FORCES

| Material | Value of Manning's n used | Velocity ft/sec | Tractive force lb/sq ft |
|---|---|---|---|
| Very light pure sand of quicksand character | 0.020 | 0.75-1.00 | 0.006-0.011 |
| Very light loose sand | .020 | 1.00-1.50 | 0.011-0.025 |
| Coarse sand or light sandy soil | .020 | 1.50-2.00 | 0.025-0.045 |
| Average sandy soil | .020 | 2.00-2.50 | 0.045-0.070 |
| Sandy loam | .020 | 2.50-2.75 | 0.070-0.084 |
| Average loam, alluvial soil, volcanic ash soil | .020 | 2.75-3.00 | 0.084-0.100 |
| Firm loam, clay loam | .020 | 3.00-3.75 | 0.100-0.157 |
| Stiff clay soil, ordinary gravel soil | .025 | 4.00-5.00 | 0.278-0.434 |
| Coarse gravel, cobbles and shingles | .030 | 5.00-6.00 | 0.627-0.903 |
| Conglomerate, cemented gravel, soft slate, tough hardpan, soft sedimentary rock | .025 | 6.00-8.00 | 0.627-1.114 |

Table 4

COMPARISON OF FORTIER AND SCOBEY'S LIMITING VELOCITIES WITH TRACTIVE FORCE VALUES

Straight Channels After Aging

| Material | n | For clear water | | Water transporting colloidal silts | |
|---|---|---|---|---|---|
| | | Velocity ft/sec | Tractive force lb/sq ft | Velocity ft/sec | Tractive force lb/sq ft |
| Fine sand colloidal | 0.020 | 1.50 | 0.027 | 2.50 | 0.075 |
| Sandy loam noncolloidal | .020 | 1.75 | .037 | 2.50 | 0.075 |
| Silt loam noncolloidal | .020 | 2.00 | .048 | 3.00 | 0.11 |
| Alluvial silts noncolloidal | .020 | 2.00 | .048 | 3.50 | 0.15 |
| Ordinary firm loam | .020 | 2.50 | .075 | 3.50 | 0.15 |
| Volcanic ash | .020 | 2.50 | .075 | 3.50 | 0.15 |
| Stiff clay very colloidal | .025 | 3.75 | .26 | 5.00 | 0.46 |
| Alluvial silts colloidal | .025 | 3.75 | .26 | 5.00 | 0.46 |
| Shales and hardpans | .025 | 6.00 | .67 | 6.00 | 0.67 |
| Fine gravel | .020 | 2.50 | .075 | 5.00 | 0.32 |
| Graded loam to cobbles when noncolloidal | .030 | 3.75 | .38 | 5.00 | 0.66 |
| Graded silts to cobbles when colloidal | .030 | 4.00 | .43 | 5.50 | 0.80 |
| Coarse gravel noncolloidal | .025 | 4.00 | .30 | 6.00 | 0.67 |
| Cobbles and shingles | .035 | 5.00 | .91 | 5.50 | 1.10 |

Table 5

USSR DATA ON PERMISSIBLE VELOCITIES FOR NONCOHESIVE SOILS

| Material | Particle diameter mm | Mean velocity ft/sec |
|---|---|---|
| | 0.005 | 0.49 |
| Silt | | |
| | 0.05 | 0.66 |
| Fine sand | | |
| | 0.25 | 0.98 |
| Medium sand | | |
| | 1.00 | 1.80 |
| Coarse sand | | |
| | 2.50 | 2.13 |
| Fine gravel | | |
| | 5.00 | 2.62 |
| Medium gravel | | |
| | 10.00 | 3.28 |
| Coarse gravel | | |
| | 15.0 | 3.94 |
| Fine pebbles | | |
| | 25.0 | 4.59 |
| Medium pebbles | | |
| | 40.0 | 5.91 |
| Coarse pebbles | | |
| | 75.0 | 7.87 |
| Large pebbles | | |
| | 100.0 | 8.86 |
| Large pebbles | | |
| | 150.0 | 10.83 |
| Large pebbles | | |
| | 200.0 | 12.80 |

Table 6

USSR CORRECTIONS OF PERMISSIBLE VELOCITY FOR DEPTH
Noncohesive Material

| | Average depth | | | | | | |
|---|---|---|---|---|---|---|---|
| Meters | 0.30 | 0.60 | 1.00 | 1.50 | 2.00 | 2.50 | 3.00 |
| Feet | 0.98 | 1.97 | 3.28 | 4.92 | 6.56 | 8.20 | 9.84 |
| Correction factor | 0.8 | 0.9 | 1.00 | 1.1 | 1.15 | 1.20 | 1.25 |

Table 7

USSR LIMITING VELOCITIES AND TRACTIVE FORCES IN COHESIVE MATERIAL

| | Compactness of bed | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Descriptive term | Loose | | Fairly | | | | Very | |
| Descriptive term | loose | | compact | | Compact | | compact | |
| Voids ratio | 2.0–1.2 | | 1.2–0.6 | | 0.6–0.3 | | 0.3–0.2 | |
| Principal cohesive | Limiting mean velocity ft/sec and limiting tractive force lb/sq ft | | | | | | | |
| Material of bed | Ft/sec | Lb sq ft | Ft sec | Lb sq ft | Ft sec | Lb sq ft | Ft sec | Lb sq ft |
| Sandy clays (sand content less than 50 percent) | 1.48 | 0.040 | 2.95 | 0.157 | 4.26 | 0.327 | 5.90 | 0.630 |
| Heavy clayey soils | 1.31 | 0.031 | 2.79 | 0.141 | 4.10 | 0.305 | 5.58 | 0.563 |
| Clays | 1.15 | 0.024 | 2.62 | 0.124 | 3.94 | 0.281 | 5.41 | 0.530 |
| Lean clayey soils | 1.05 | 0.020 | 2.30 | 0.096 | 3.44 | 0.214 | 4.43 | 0.354 |

Table 8

USSR CORRECTIONS OF PERMISSIBLE VELOCITY FOR DEPTH
Cohesive Materials

| Average depth | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Meters | 0.3 | 0.5 | 0.75 | 1.0 | 1.5 | -2.0 | 2.5 | -3.0 |
| Feet | 0.98 | 1.64 | 2.46 | 3.28 | 4.92 | -6.56 | 8.20 | -9.84 |
| Correction factor | 0.8 | 0.9 | 0.95 | 1.0 | 1.1 | -1.1 | 1.2 | -1.2 |

Table 9

TENTATIVELY RECOMMENDED LIMITING VALUES OF TRACTIVE FORCE FOR CANALS IN FINE, NONCOHESIVE MATERIAL

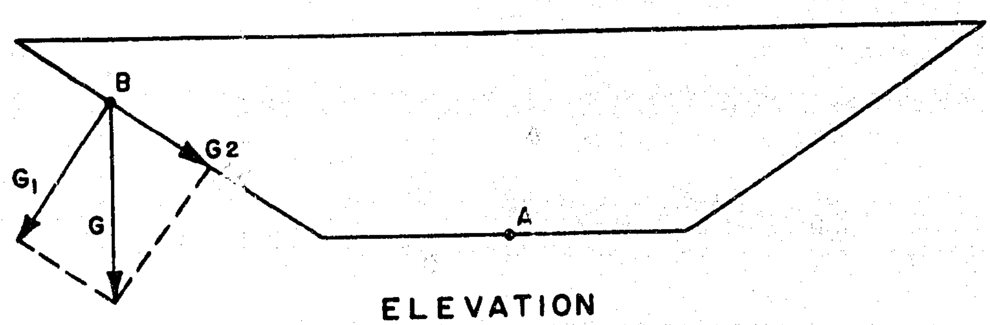
| Median size of material mm | Limiting tractive force lb/sq ft | | |
|---|---|---|---|
| | Clear water | Light load of fine sediment | Heavy load of fine sediment |
| 0.1 | 0.025 | 0.050 | 0.075 |
| 0.2 | .026 | .052 | .078 |
| 0.5 | .030 | .055 | .083 |
| 1.0 | .040 | .060 | .090 |
| 2.0 | .060 | .080 | .110 |
| 5.0 | .140 | .165 | .185 |

Table 10

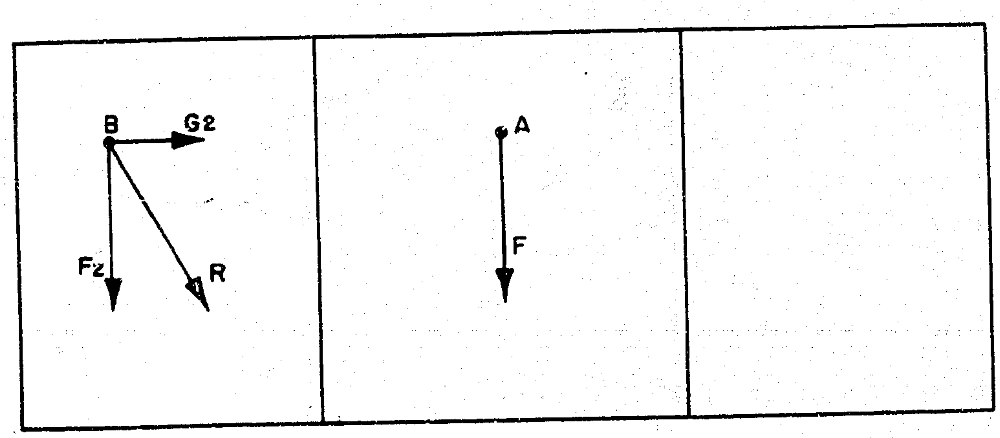
TRACTIVE FORCES IN SINUOUS CANALS

| Degree of sinuosity | Relative tractive force (percent) | Corresponding relative velocity (percent) |
|---|---|---|
| Straight canals | 100 | 100 |
| Slightly sinuous canals | 90 | 95 |
| Moderately sinuous canals | 75 | 87 |
| Very sinuous canals | 60 | 78 |

FIGURE 1

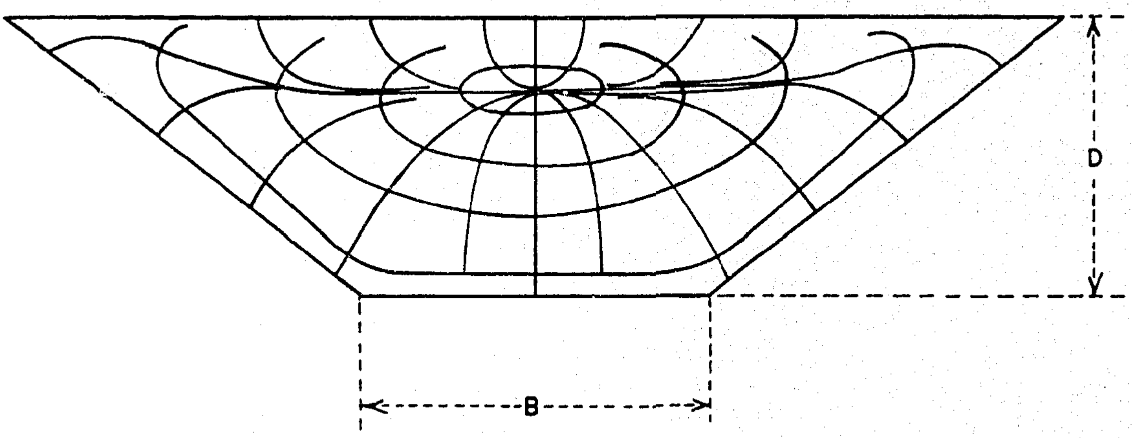



ELEVATION

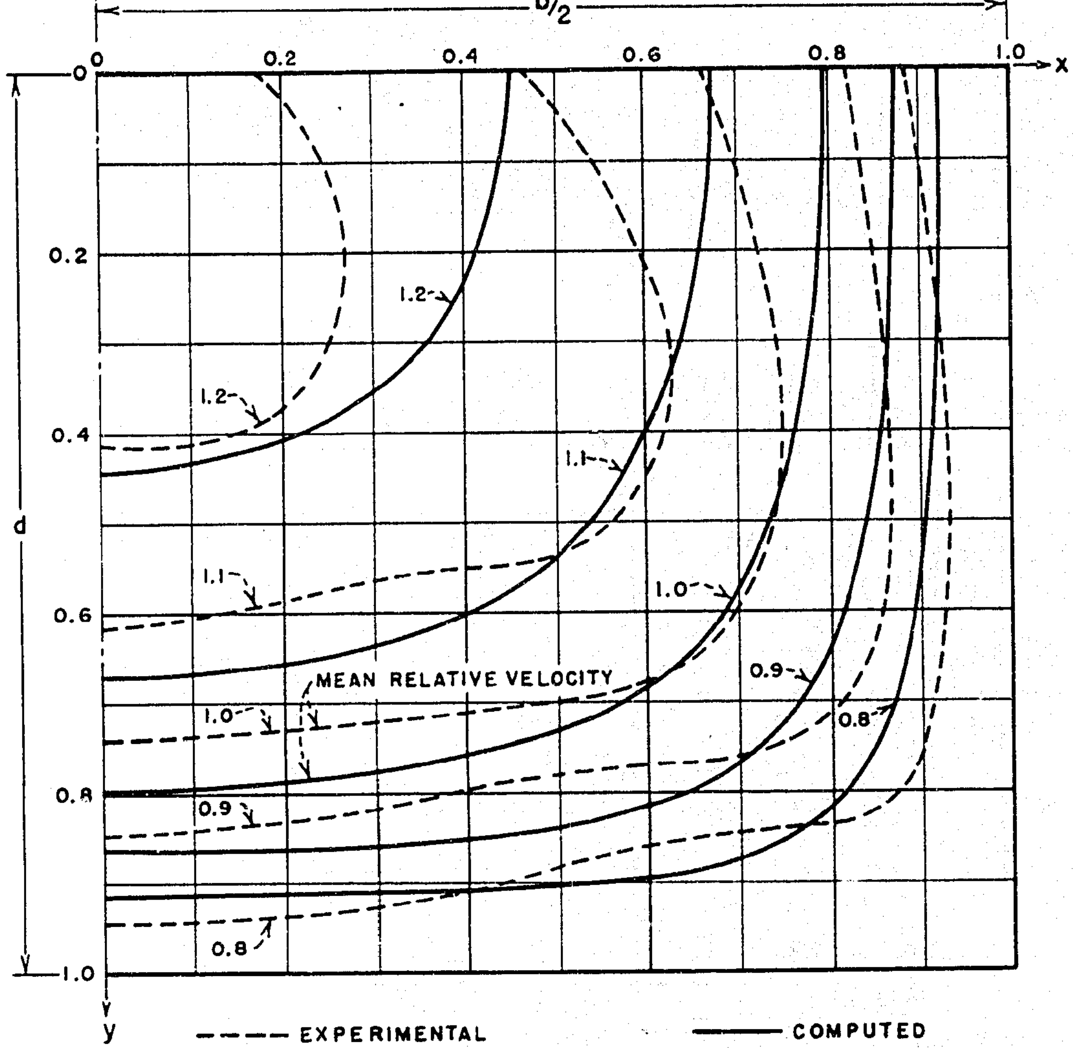



PLAN

FIGURE 2




VELOCITY DISTRIBUTION AND ORTHOGONAL LINES
OF A TYPICAL CANAL CROSS SECTION

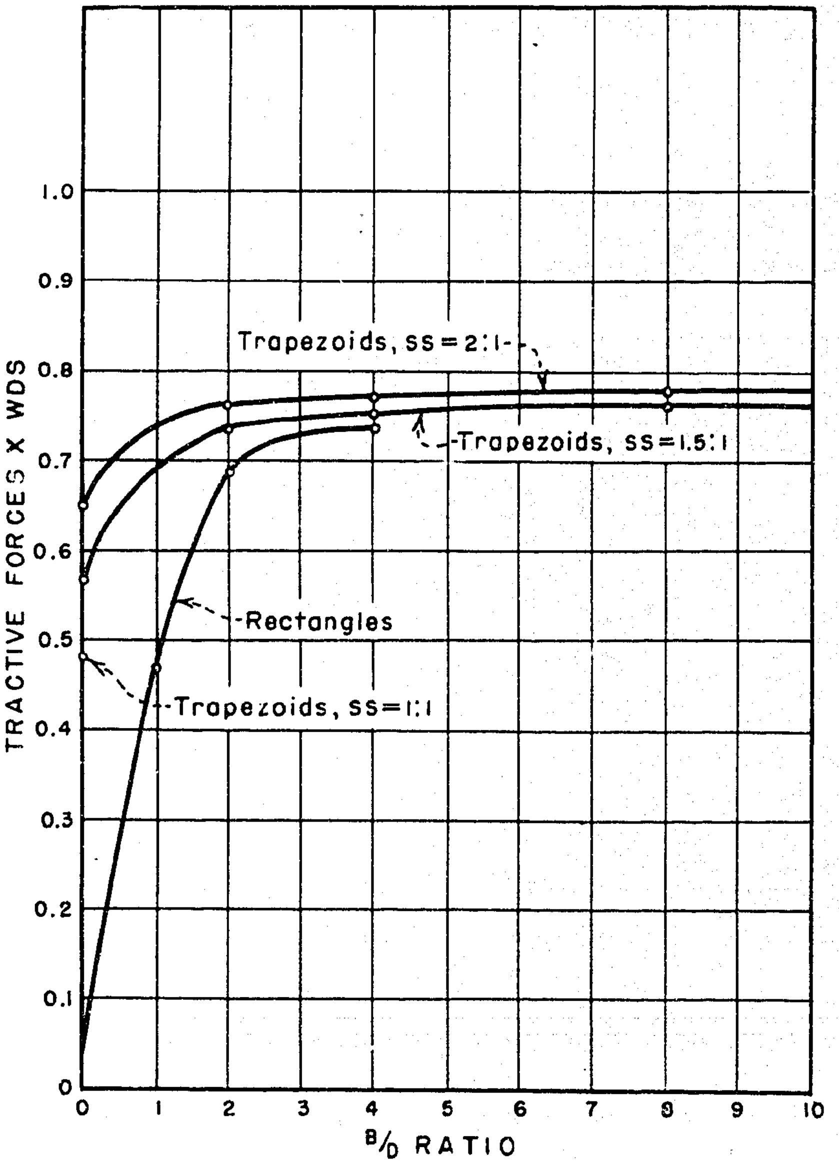



SHEAR PROPORTIONAL TO GRADIENT OF $V^4$

VELOCITY DISTRIBUTION IN A RECTANGULAR CHANNEL

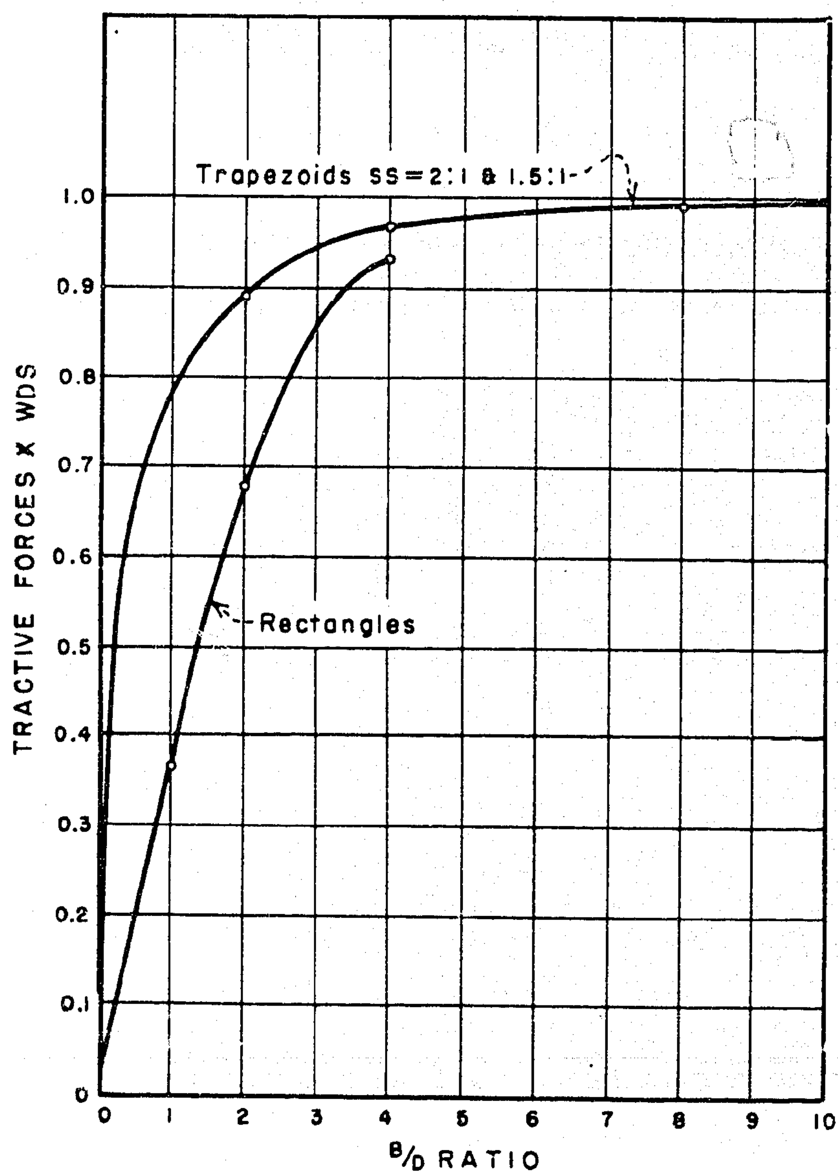
b = 2d

FIGURE 4




MAXIMUM TRACTIVE FORCES IN TERMS OF WDS
ON SIDES OF CHANNELS

FIGURE 5




MAXIMUM TRACTIVE FORCES IN TERMS OF WDS ON BOTTOM OF CHANNELS

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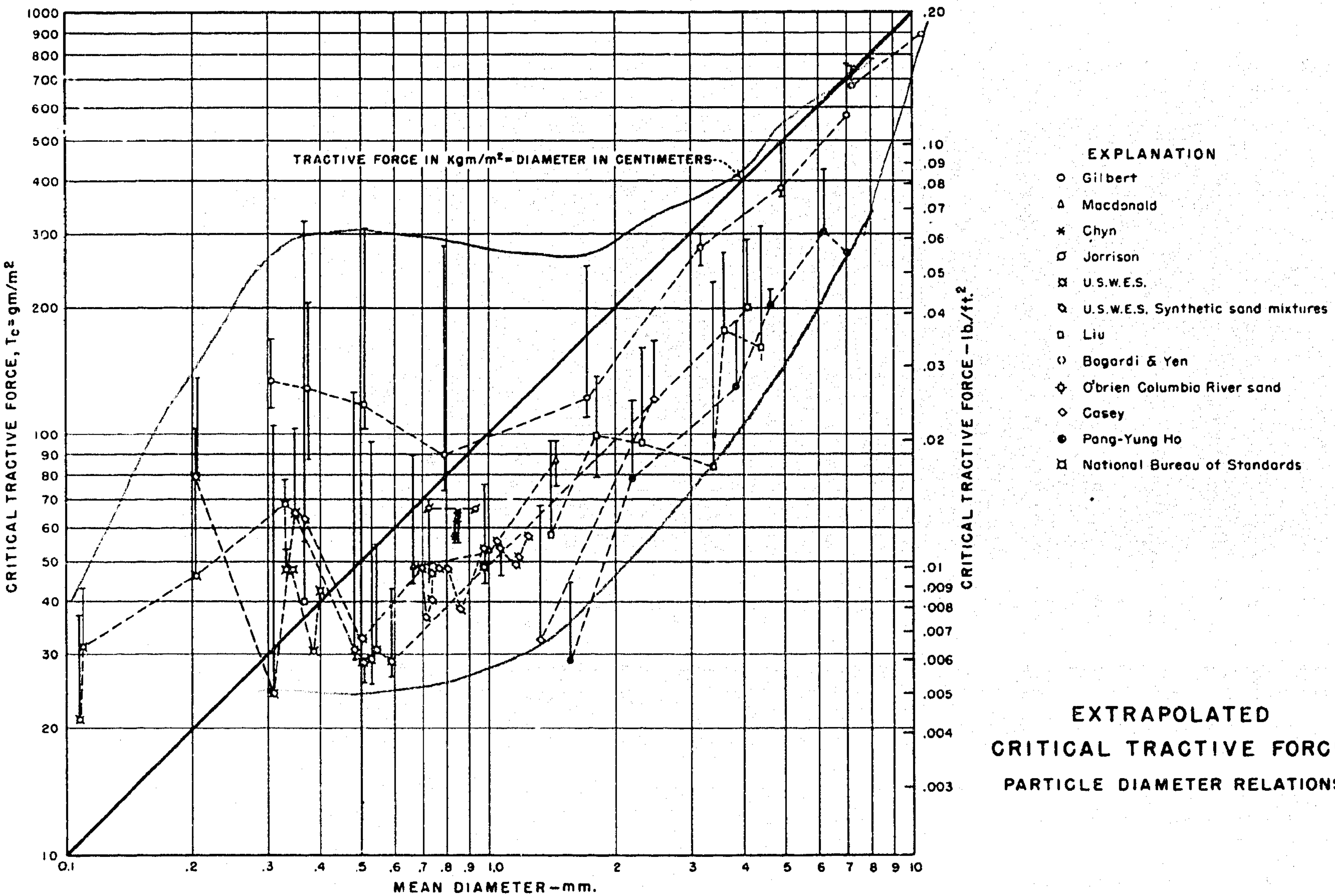
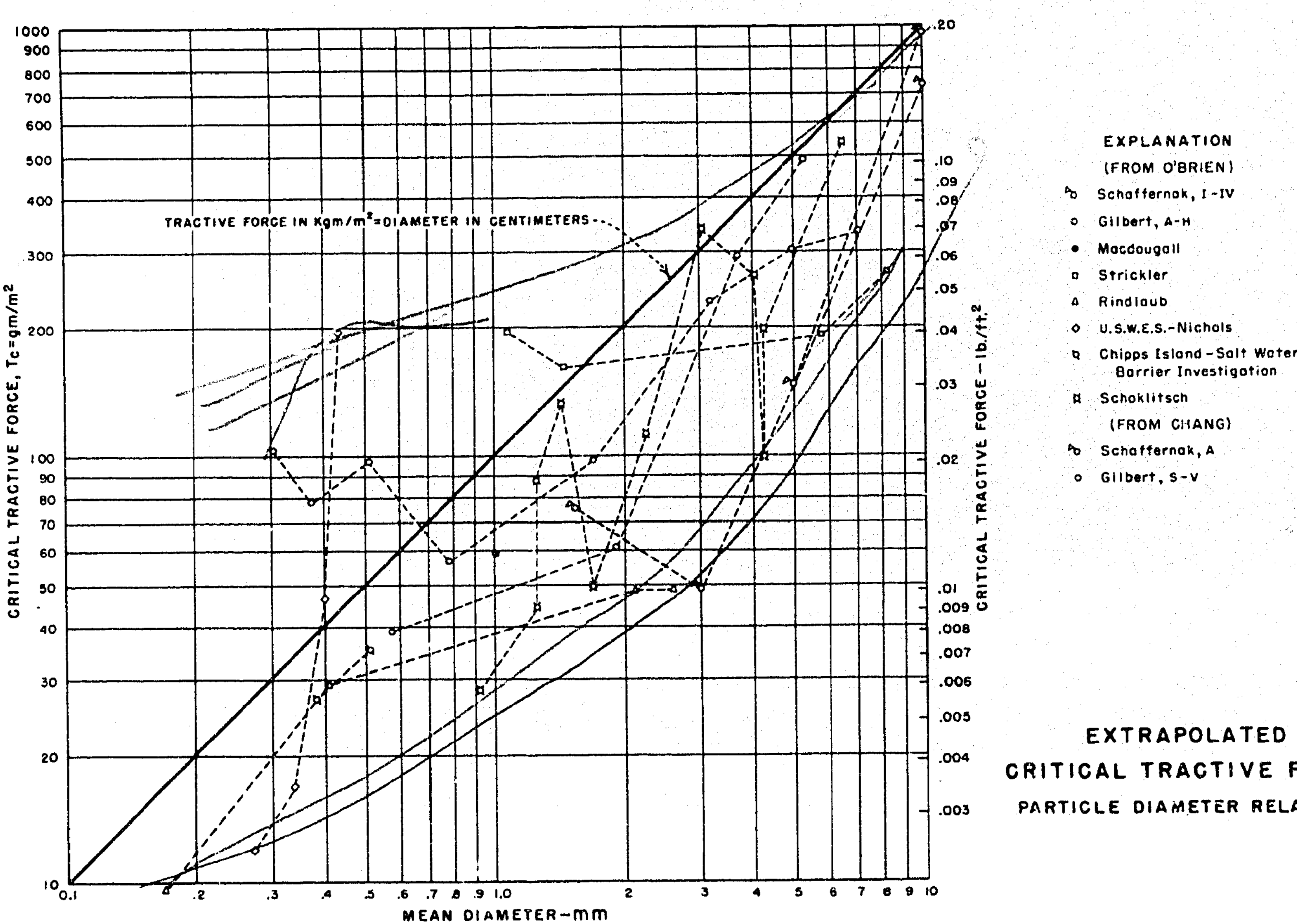
FIGURE 6




EXTRAPOLATED
CRITICAL TRACTIVE FORCE
PARTICLE DIAMETER RELATIONS




EXTRAPOLATED
CRITICAL TRACTIVE FORCE
PARTICLE DIAMETER RELATIONS

FIGURE 7

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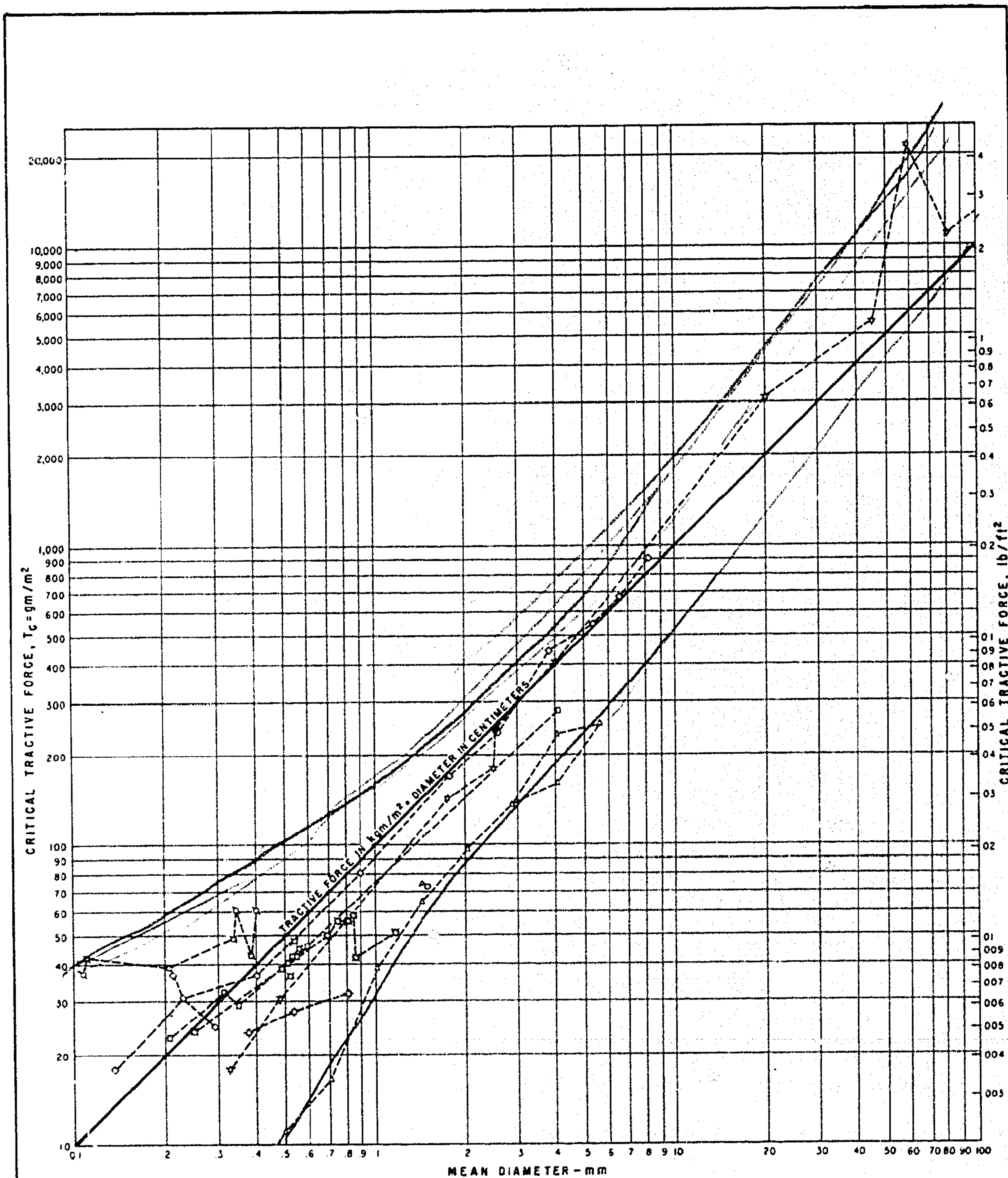
FIGURE 8




EXPLANATION

- U.S.W.E.S. (1)
- Chang (1)
- National Bureau of Standards (1)
- Kramer (1)
- Indri (1)
- Chitty Ho (2)
- Krey (3)
- Prussian Experimental Institute (1)
- Engels (1)
- (1) General movement
- (2) Initial movement
- (3) Criterion unknown

**OBSERVED**

**CRITICAL TRACTIVE FORCES**

**FLUME STUDIES**

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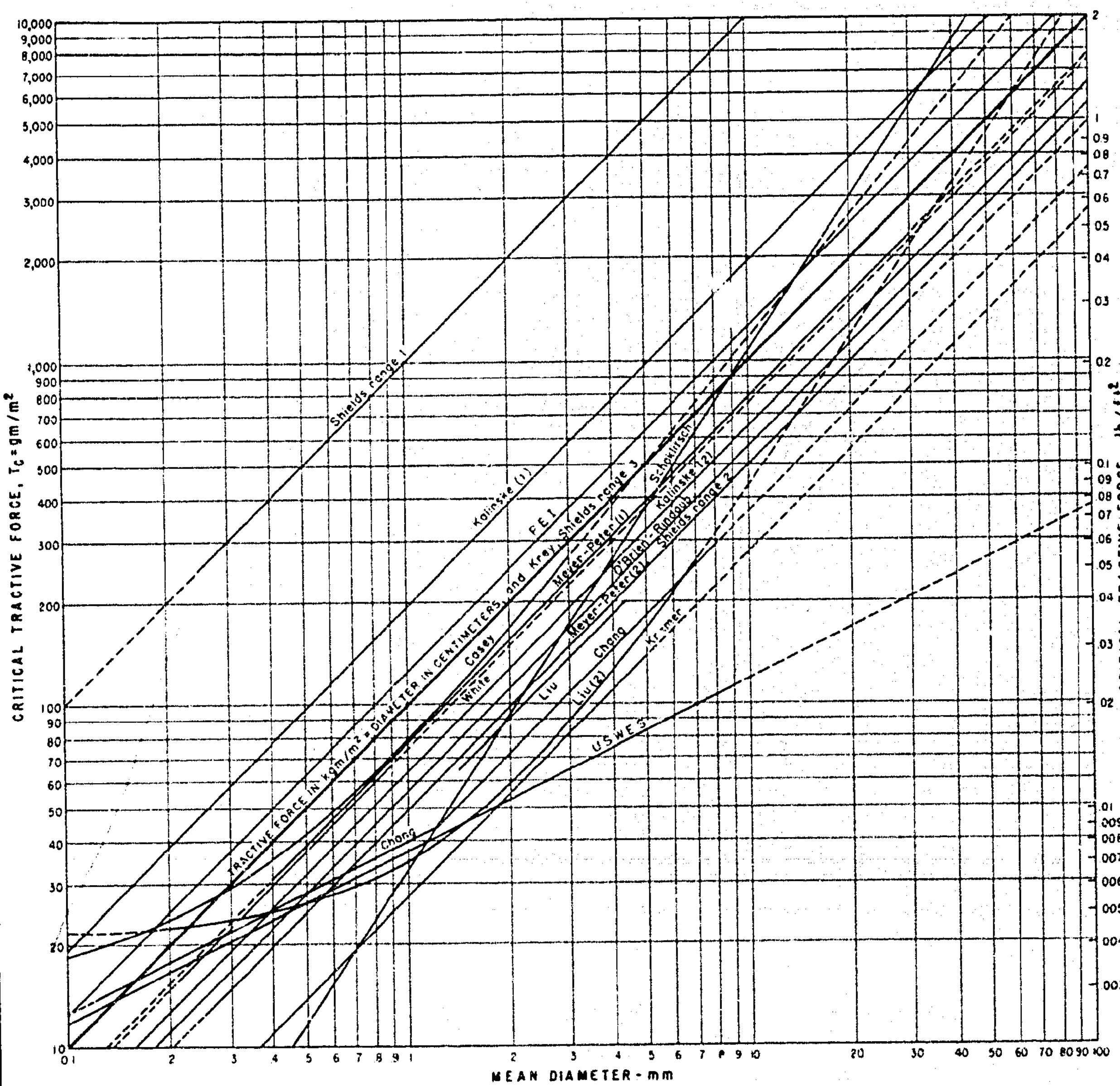


CRITICAL TRACTIVE FORCE

FORMULAE

ASSUMPTIONS

SAND: M = 1.0
P = 2.65

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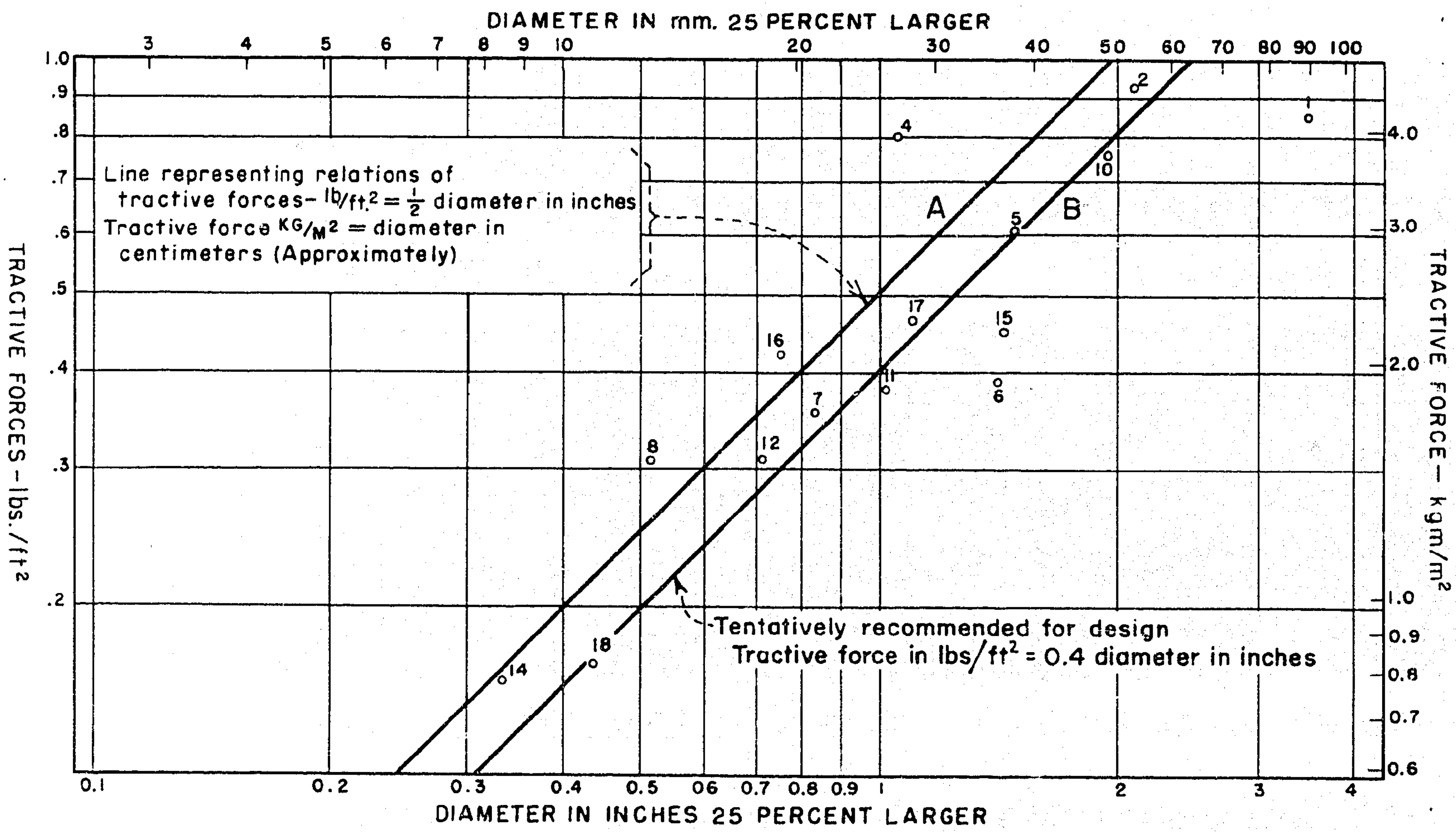
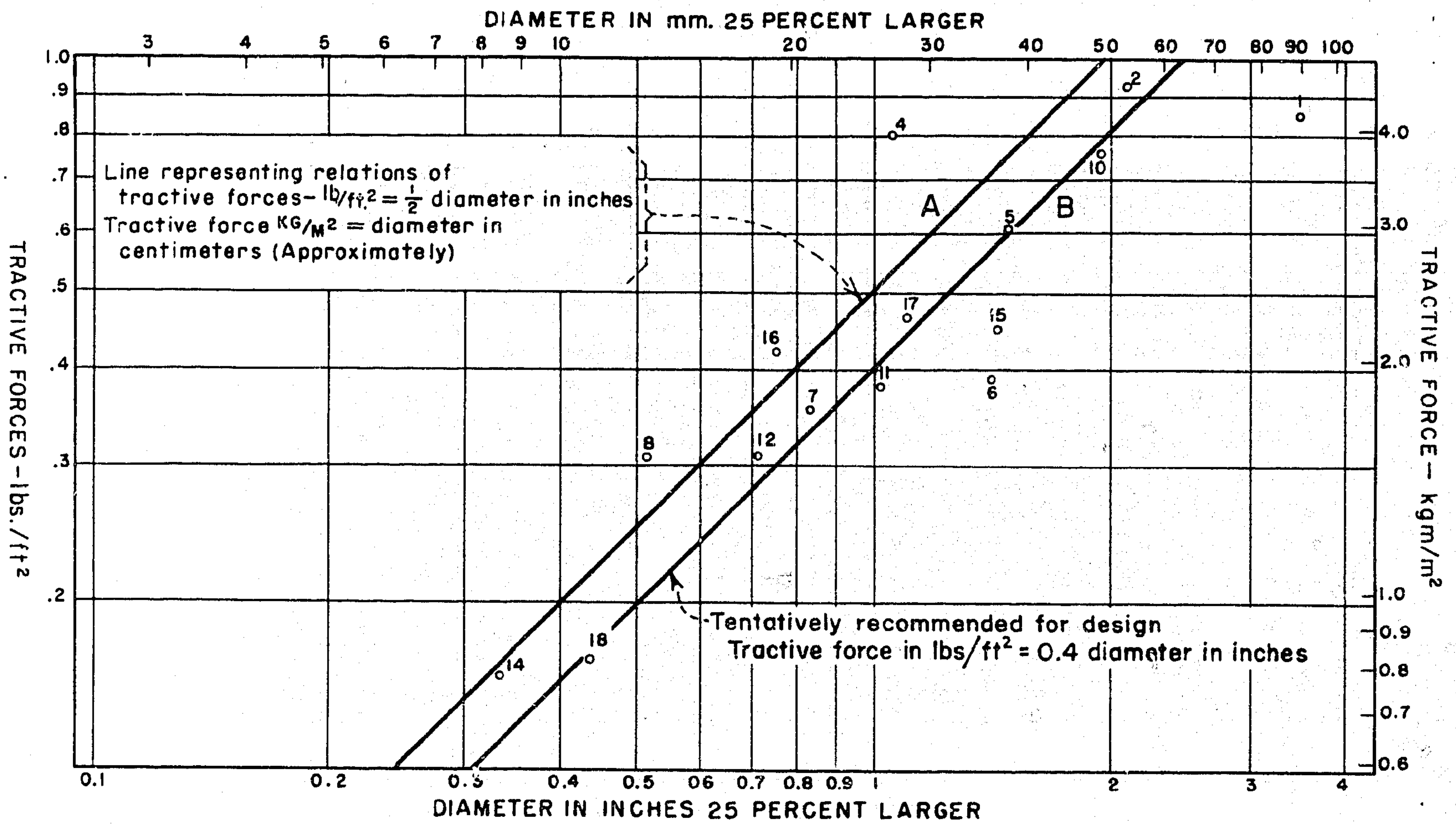



RESULTS OF STUDIES ON SAN LUIS VALLEY CANALS

FIGURE 10




RESULTS OF STUDIES ON SAN LUIS VALLEY CANALS

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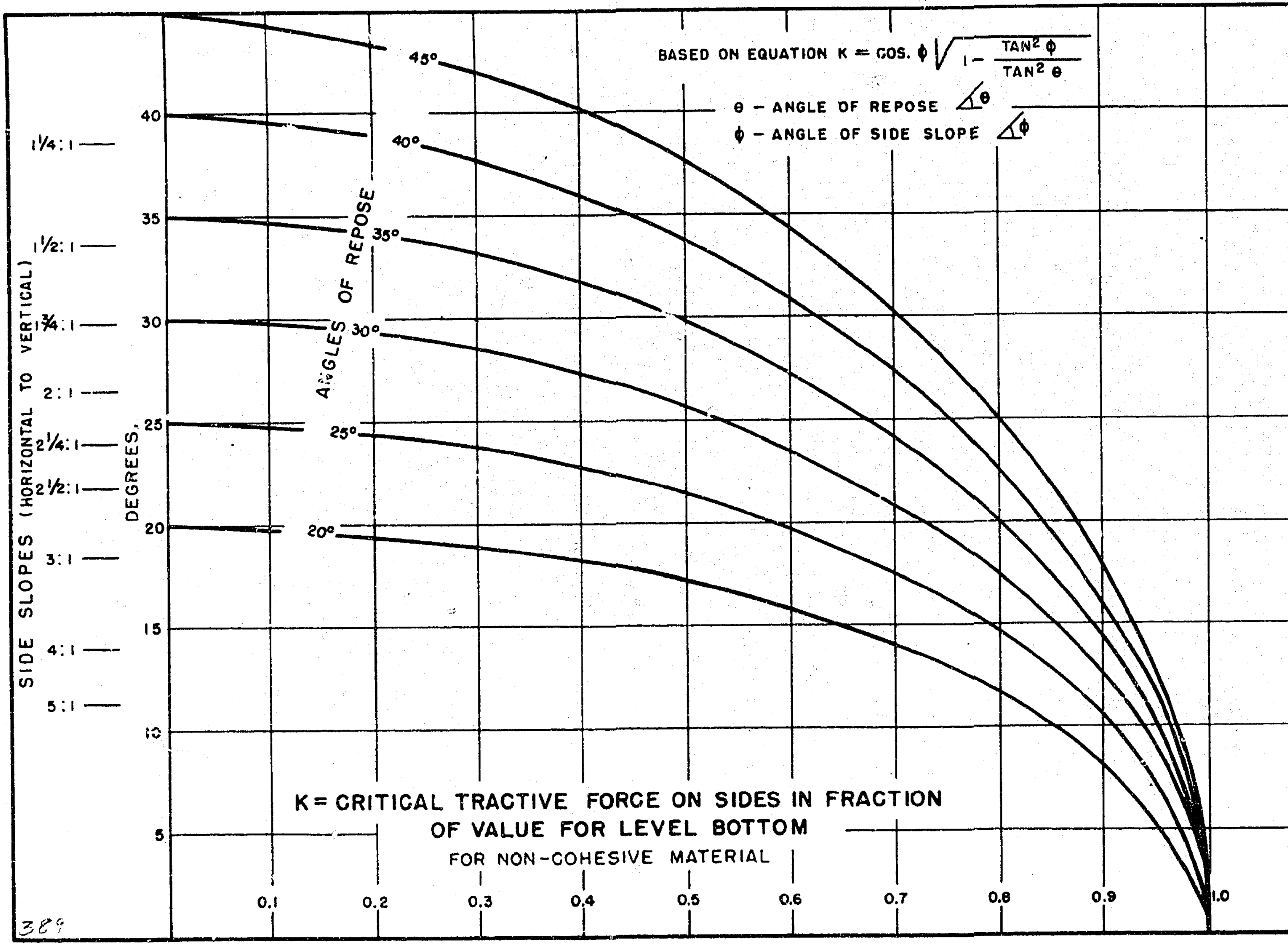
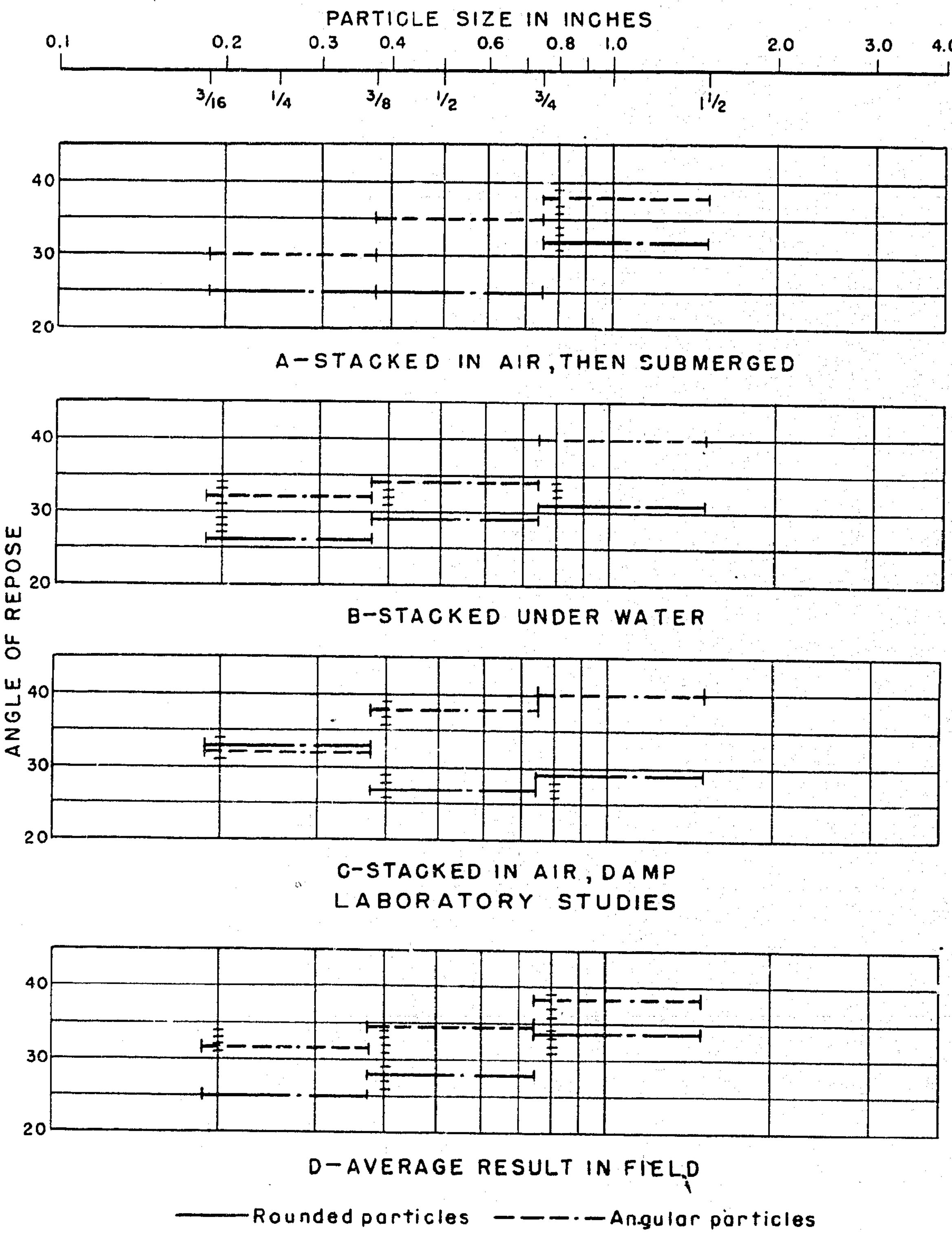



FIGURE 11

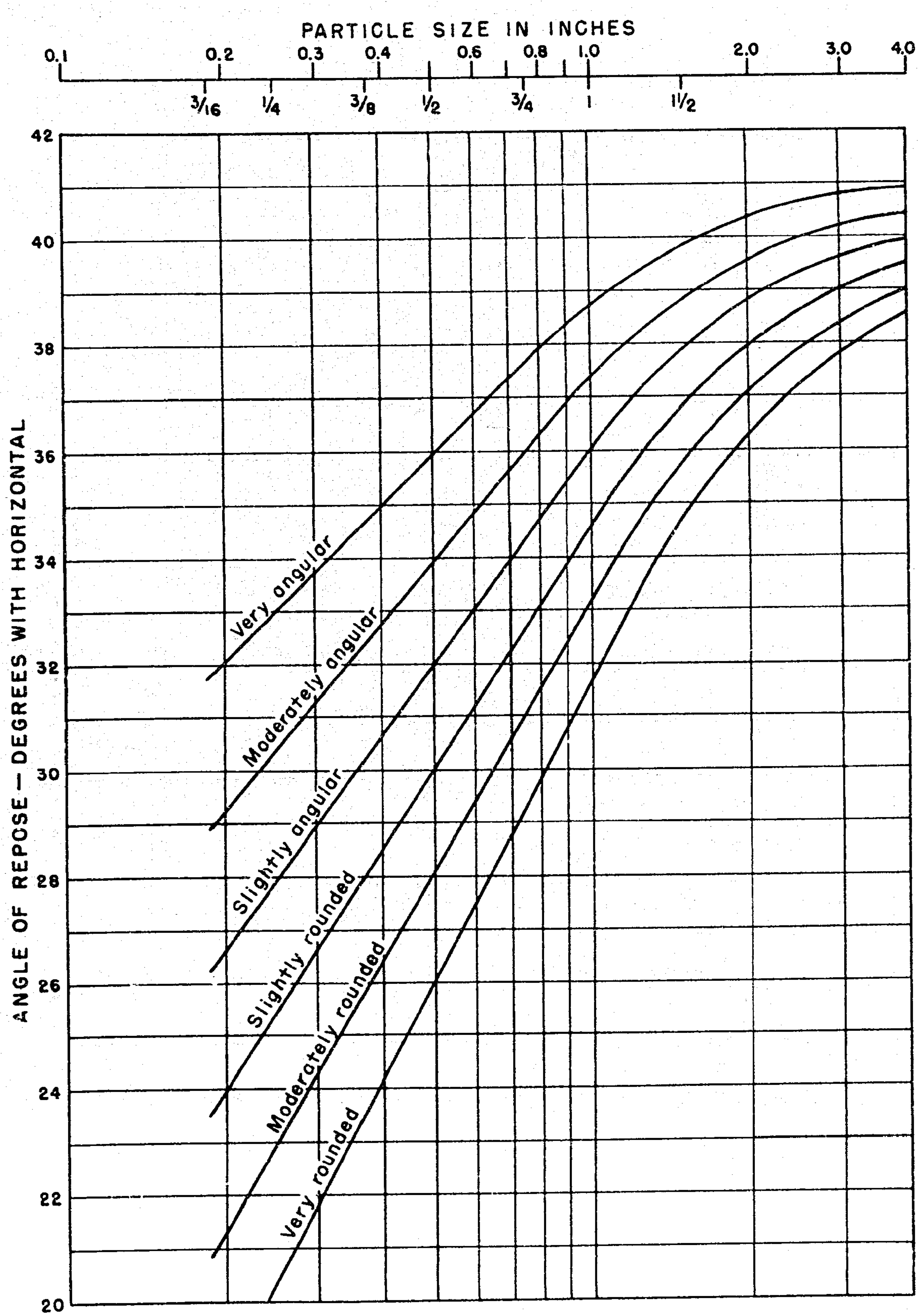
7-1-51

FIGURE 12



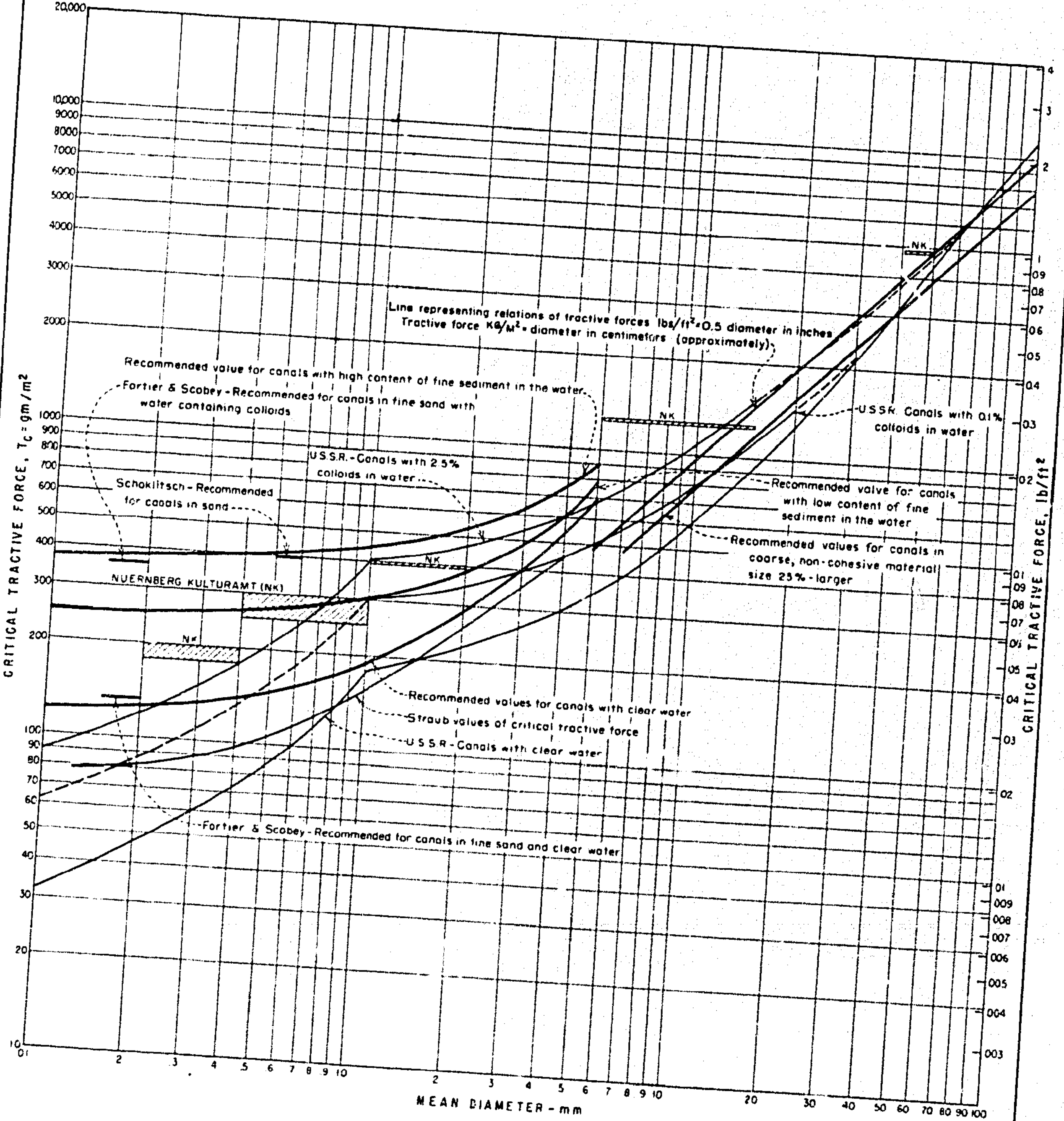

RESULTS OF OBSERVATIONS ON ANGLE OF REPOSE OF COARSE NON-COHESIVE MATERIAL

FIGURE 13




ANGLES OF REPOSE OF NON-COHESIVE MATERIAL

FIGURE 14




LIMITING TRACTIVE FORCES
RECOMMENDED FOR CANALS
AND
OBSERVED IN RIVERS